Late Quaternary Development of a deep-water Carbonate Mound in the northeast Atlantic

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ABSTRACT

Over the last decade, numerous morphologically positive structures elevated up to several hundred meters above the surrounding seafloor, have been discovered along the NW European Continental Margin in 1200 to 600m water depth. These structures are commonly referred to as carbonate mounds, which are often covered by thickets of the ahermatypic corals *Lophelia pertusa* and *Madrepora oculata*, making them morphologically diverse bioherms. Complex interaction of active biological, sedimentological and hydrological processes indicates a close connection between the carbonate mounds and cold-water corals. Numerous seismic, sonar and video observations have been carried out on these mounds, but here the first detailed study on sediment cores from a carbonate mound in the northeast Atlantic is presented.

In a case study on Propeller Mound, detailed investigations have been carried out on gravity cores with the intention to assess its carbonate budget, to identify sedimentary processes and to reconstruct paleoenvironmental and paleoclimatological conditions. Propeller Mound is a ~150m elevated mound in the Porcupine Seabight ca. 90 nautical miles west off South-Ireland. In total 6 gravity cores (3.5 to 6m long) from Propeller Mound and adjacent areas have been analysed geochemically and micro-paleontologically. In addition, the coral contents have been analysed for the sediments retrieved from the mound itself to estimate their impact on sedimentation.

The carbonate budget shows that Propeller Mound is indeed a carbonate mound – with a $CaCO_3$ content in the sediments >50 wt.-% for the last 175kyrs. In contrast, the sediments from the reference sites off Propeller Mound contain <37 wt.-% carbonate for Holocene and <23 wt.-% carbonate for glacial sediments. The approximately 30 wt.-% difference between the mound and reference locations represents the carbonate input due to aragonite added to the mound sediments by the corals. It is contributed either as fragments or reworked as a component of the fine fraction. Although the corals even add material to normal background sedimentation, budget calculations show that only ~5% carbonate and bulk-sediment accumulates on the mound compared to the reference sites. The net long-term accumulation rates on Propeller Mound are comparably low due to several extended hiatuses in the sedimentary record. Stable oxygen isotope data in combination with Accelerator Mass Spectrometry (AMS) ^{14}C and U/Th ages show that glacial and interglacial sediments were either not deposited or were later eroded on the mound. Instead, almost exclusively interstadial sequences have been preserved.

These sediments are characterised by large fragments of cold-water corals embedded in a matrix dominated by mud. Fragments of the coral species *Lophelia pertusa* are abundant, and fragments of *Madrepora occulata* are also common, creating a loose coral framework that stabilises the soft sediments. Erosion of the interglacial and glacial sediments occurred due to enhanced currents during interglacials caused by the northward flowing branch of the Mediterranean Outflow Water (MOW).

MOW is the dominant water mass affecting the mounds in the Porcupine Seabight. Topographically steered, it enters the Porcupine Seabight and circulates cyclonically between 800 and 600m water depth. The influence of the MOW is also well documented in benthic foraminiferal assemblages found on-mound with distinct similarities to assemblages found in the Mediterranean Sea. During glacials MOW did not enter the Porcupine Seabight. It was replaced by cold water masses from the north. Low water temperatures (benthic foraminifera indicate values below 4°C), enhanced sediment input from the shelf and the input of Ice Rafted Detritus (IRD) created an environment unfavourable for corals and indeed no corals have yet been reported from sediments of the Last Glacial Maxima (LGM). Instead, unconsolidated fine grained sediments capped the mound during such glacial intervals.

When the MOW circulation was re-established during the deglaciation, the glacial sediments became destabilised and winnowing, erosion and mass wasting on the mound condensed the sedimentary record. Horizons enriched in coarse material are the only remaining records of glacial sediments deposited on the mound. Only coral bearing sediments deposited during interglacials have had the potential of being preserved. No sediments were preserved from times when corals have been absent from the mound.

Winnowing and mass wasting on one hand and sediments stabilised by corals on the other hand result in a spatially and temporally complex sedimentary record. It is therefore impossible to correlate the hiatuses or the remaining sediments on Propeller Mound.

In contrast to on mound sediments, those deposited in the areas adjacent to Propeller Mound contain more or less continuous and easily correlatable records. They extend back to late oxygen isotope stage 3, representing ~30kyr in ~4 core meters.

The discrepancy between sediments from Propeller Mound and the adjacent area imply that at least for the last ~300kyrs Propeller Mound has been shrinking. The mound is currently on the decline and if this trend persists, will be buried at some point in the future, like the already buried Magellan Mounds ca. 10 nautical miles further to the north.

ZUSAMMENFASSUNG

Im Laufe der letzten 20 Jahre sind entlang des europäischen Kontinentalhanges in Wassertiefen zwischen 600–1200m zahlreiche bis zu 350m hohe Erhebungen entdeckt worden. Bei diesen handelt es sich um so genannte 'Carbonate Mounds' – häufig assoziiert mit Dickichten ahermatyper Kaltwasserkorallen. Das verstärkte Auftreten der Korallen, hauptsächlich den beiden Arten *Lophelia pertusa* und *Madrepora oculata*, auf den Mounds und der hohe Anteil an Korallenbruchstücken in Mound-Sedimenten legen die Vermutung nahe, dass Korallen maßgeblich an der Entstehung der Mounds beteiligt sind. Doch obwohl die Bedeutung der Korallen früh erkannt worden ist, hat es bis jetzt noch keinen Versuch gegeben ihren Einfluss zu quantifizieren. Auch sind viele der komplexen Wechselbeziehungen zwischen den Korallen, den Mounds und den vorherrschenden hydrographischen Bedingungen noch nicht hinreichend untersucht. Die hier vorliegende Arbeit stellt daher den ersten Versuch dar, anhand eines Karbonatbudgets, exemplarisch für einen Carbonate Mound, den Korallenanteil an den Moundsedimenten und den Korallen-einfluss auf die Mounds zu quantifizieren. Des Weiteren haben geochemische und mikropaläontologische Untersuchungen dazu beigetragen, die komplexen Wechsel-beziehungen zwischen Korallen, Hydrographie und Sedimentologie zu verdeutlichen, und somit zu einem besseren Verständnis der Entwicklung dieses Carbonate Mounds geführt.

Untersucht worden ist ein ca. 150m hohe Erhebung in der Porcupine Seabight – der Propeller Mound. Er befindet sich etwa 90 Seemeilen westlich von Südirland und ist Teil einer Gruppe von Mounds, die Hovland Mound Provinz genannt wird. Um die Entwicklung des Propeller Mounds während des Spätquatärs zu rekonstruieren, sind insgesamt sechs zwischen 3.5 und 6m lange Schwerelote gekernt worden. Drei Schwerelotkerne stammen vom Mound, während drei weitere in der unmittelbaren Umgebung des Mounds gewonnen worden sind und als Referenzkerne zur Rekonstruktion der Hintergrundbedingungen dienen.

Die Budgetberechungen für den Propeller Mound zeigen, dass es sich im wahrsten Sinne des Wortes um einen “Karbonat Hügel“ handelt. Alle Sedimente vom Mound bestehen zu mehr als 50 Gew.-% aus Kalziumkarbonat. Im Gegensatz dazu enthalten die Referenz-sedimente im Holozän maximal 37 Gew.-% und im Glazial nur maximal 23 Gew.-% Karbonat. Bei den etwa 30 Gew.-% Differenz handelt es sich um den Karbonatanteil, der durch Korallen zusätzlich in das Sediment eingetragen worden ist. Dies ist zum einen in Form großer Korallenfragmente geschehen, zum anderen aber auch als fein aufgearbeiteter Karbonatschlamm. Obwohl durch die Korallen zusätzliches Karbonat in das Sediment gelangt ist, und in den Korallendickichten zudem die Sedimentation begünstigt gewesen ist, hat sich gezeigt, dass während der letzten 300.000 Jahre im Vergleich zu den Referenzlokationen nur ein Bruchteil (~5%) an Sediment und Karbonat auf dem Mound akkumuliert worden ist.

Absolute Altersdatierungen sowie sedimentologische Analysen und Untersuchungen an stabilen Sauerstoffisotopen haben jedoch gezeigt, dass auf dem Mound nicht primär die Akkumulation, sondern in hohem Maße auch die Erhaltung, die Sedimente beeinflusst. So hat sich herausgestellt, dass die Sedimentabfolgen auf dem Mound, anders als in den benachbarten Gebieten, nicht kontinuierlich sind. Sie sind vielmehr durch das Auftreten mehrerer Hiaten unterbrochen. Starke Bodenströmungen haben dazu geführt, dass am Propeller Mound fast ausschließlich interstadiale Sequenzen erhalten geblieben sind. Glaziale und interglaziale Sedimente sind entweder nicht abgelagert oder zu einem späteren Zeitpunkt wieder erodiert worden.

Im Rezenten werden erosive Bodenströmungen durch das nordwärts fließende Mittelmeerausstromwasser (MOW) erzeugt. Während der Glaziale, wenn der Mittelmeerausfluss verringert ist, wird das MOW im Bereich der Mounds durch eine langsam fließende kalte Zwischenwassermasse aus dem Norden ersetzt. Niedrige Wassertemperaturen (<4°C) und vermehrter Sedimenteintrag führen dazu, dass sich die Korallen aus der Porcupine Seabight zurückziehen, und der Propeller Mound von unkonsolidierten feinen Sedimenten überdeckt wird. Wenn sich das MOW im Interglazial wieder in der Porcupine Seabight etabliert, und sein Einfluss auf die Mounds zunimmt, wird aus den glazialen Sedimenten die Feinfraktion ausgeblasen. Erhalten bleibt nur die Grobfraktion, die sich in Lagen anreichert und dadurch die Positionen der Hiaten kennzeichnet.

Da sich jedoch weder die Hiaten noch die auf dem Mound verbliebenen Sedimente korrelieren lassen, müssen neben dem Ausblasen weitere Prozesse die Sedimenterhaltung beeinflussen. Sehr wahrscheinlich ist, dass Erosion an den Flanken des Mounds die unkonsolidierten glazialen Sedimente destabilisiert und lokale Hangrutschungen stattfinden. Diese lokalen Prozesse und das unterschiedliche Erhaltungspotenzial der Sedimente würden die hohe räumliche und zeitliche Variabilität erklären, die in den Sedimenten vom Propeller Mounds dokumentiert ist.

Abschließend ist anzumerken, dass die geringe Sedimenterhaltung auf dem Propeller Mound während der letzten ca. 300.000 Jahre dazu geführt hat, dass dieser relativ zu den umliegenden Gebieten geschrumpft ist. Falls dieser Trend weiter anhält, ist zu erwarten, dass der Propeller Mound irgendwann vollständig durch die Hintergrundsedimentation überdeckt sein wird. In diesem Fall würde er das Schicksal der Magellan Mounds teilen, einer Gruppe versunkener Mounds, die sich ca. 10 Seemeilen nördlich des Propeller Mounds befinden.

INTRODUCTION

1.1 MOTIVATION AND MAIN OBJECTIVES

Recently discovered giant carbonate mounds along the western European continental margin overgrown by dense thickets of ahermatypic cold water corals (Hovland et al. 1994; De Mol et al. 2002; Kenyon et al. 2003) challenge the general opinion of coral reefs occurring exclusively in shallow waters of the lower latitudes. At water depths ranging from 1200 to 600m, the cold water coral reefs thrive in permanent darkness at ~8°C water temperature rivalling their tropical counterparts in terms of species richness and diversity (Jensen and Frederiksen 1992; Rogers 1999; Freiwald 2002).

Within the last several decades more and more morphologically positive features identified as carbonate mounds have been reported either on the basis of bathymetric or seismic data along the Northeast Atlantic Margin (Hovland et al. 1994; De Mol et al. 2002; van Rooij et al. 2003). Known to fishermen for more than a century (Teichert 1958) these mounds have quite recently regained scientific attention. Early scientific interest in the mounds arose at the beginning of the 20th century and was primarily limited to biologists studying the deep-water corals and associated faunas (Gravier 1908; Joubin 1922). Renewed and wider interest in the morphology and generative processes of the carbonate mounds originated late last century when Hovland et al. (1994) published an article on carbonate knolls in the Porcupine Seabight and postulated a possible link between those knolls/mounds and hydrocarbon seepage.

Bottom sampling in the Porcupine Seabight proved the existence of coral reefs (Dons 1944) or coral reef mounds (Mullins et al. 1981). Hovland et al. (1994) interpreted positive features on seismic profiles to be carbonate knolls or bioherms. Another widely used term for these structures is that of a coral bank (Teichert 1958; Stetson et al. 1962; Squires 1964) or a carbonate mound (De Mol et al. 2002). The previously listed names indicate the close connection between these build-ups and cold water corals and it is confirmed in literature that the majority of these coral banks/mounds are constructed by the framework builder *Lophelia spp* and associated fauna (Jensen and Frederiksen 1992; Mortensen et al. 1995; Freiwald and Wilson 1998; Rogers 1999). In the course of increasing commercial interests from the oil and fishing industries which nowadays pose as a real threat to this ecosystem, scientific interest has again been drawn to the mounds. This renewed attention has so far resulted in the formation of three EU-projects (ECOmound – focusing on external factors active on carbonate mounds; GEOmound – investigating geological controls on mound formation;

ACES – devoted to the faunal communities established on carbonate mounds), focusing almost exclusively on these mounds and the corals.

Since the beginning of these projects, extended surveys have been carried out reporting an ever increasing number of mounds along the European Margin (Fig. 1.1). It has been found that these mounds are not randomly distributed but occur in high densities in distinct provinces. The Darwin Mounds, for example are a province of small mounds (only up to 10m high) in the Northern Rockall Trough (Masson et al. 2003) while provinces of later discussed giant carbonate mounds (up to 350m high) are located on the eastern and western slopes of the Rockall Trough (Kenyon et al. 2003; van Weering et al. 2003) or in the Porcupine Seabight (De Mol et al. 2002; Huvenne et al. 2002; 2003; van Rooij et al. 2003).

All these mound provinces have been intensively mapped, but in contrast to the immense amount of descriptive data, hardly any information exists about the development of these mounds. Most of the processes active on carbonate mounds are still unknown. The steering-factors for mound growth have not yet been identified and only two general hypotheses are recently under controversial discussion regarding their development.

1) The initial hypothesis of Hovland et al. (1994) postulate a link between the carbonate mounds and seepage of light hydrocarbons. According to this hypothesis mounds occur in areas with active hydrocarbon formation and form above deep-seated faults which act as migration path ways for fluids and gases. The theory is further supported by the observations of Hovland et al. (1994) and Henriet et al. (1998; 2002) that some mounds do form in areas of seepage. The presence and decay of recent and residual gas hydrates is also discussed as an additional energy source for chemosynthetic microbial communities. These have been postulated to be the precursors of reef communities in deep water (Henriet et al. 1998; Henriet et al. 2002; MacDonald et al. 2003), thus initiating and supporting mound growth. The weakness of this theory is that so far no clear indications of past migration, as columnar disturbances (Hovland and Judd 1988) or escape structures have been observed on seismic profiles below any carbonate mounds (De Mol et al. 2002).

2) More recent theories contrary to the seepage hypothesis assume the mounds to be primarily steered by oceanographic and biological factors. Following these approaches the presence of carbonate mounds is considered to be closely related to hydrography and living conditions favourable for the azooxanthellate corals. Nutrient supply, current activity and slow sedimentation rates are expected to be key factors (Stetson et al. 1962; Cairns and Stanley 1981; Mullins et al. 1981; Frederiksen et al. 1992; Mortensen et al. 1995; Freiwald et al. 1999), influencing mound development.

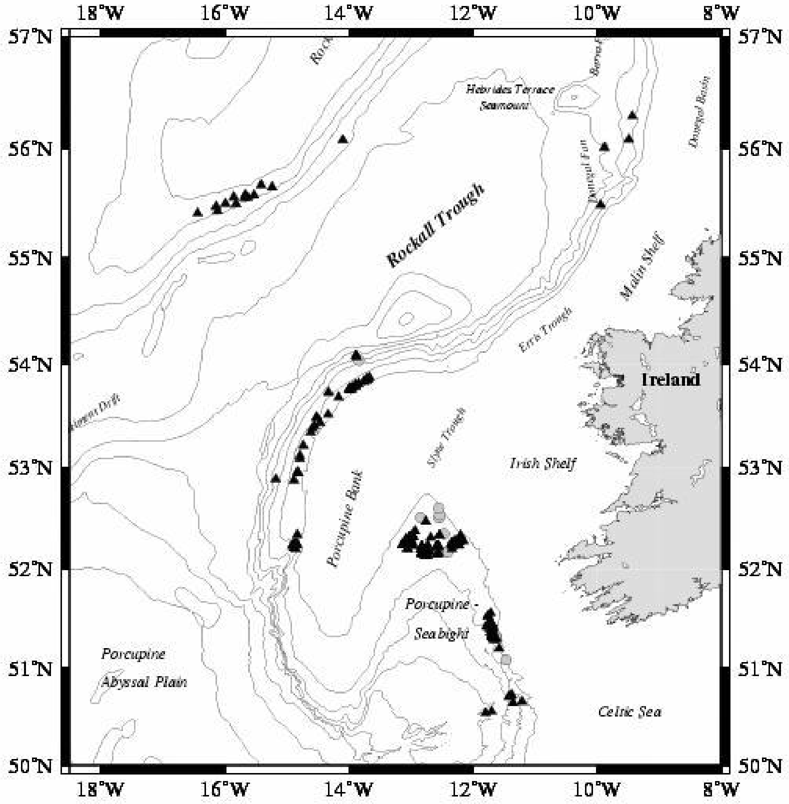

Fig. 1.1 Distribution of carbonate mounds in the Porcupine Seabight and the Rockall Trough. Triangles indicate exposed mounds, while circles mark buried mounds (from Croker and O'Loughlin 1998).

Further on, no quantification of carbonate in mound sediments has so far been carried out, even though their high abundance and their lateral extension with substantial extent below the seafloor make them a significant contributor of volume to the sedimentary system of the Western European Margin. Taking into account the fact that these mounds contain significant volumes of calcium carbonate raises the question – to what extend do they contribute to the global carbonate budget? Together with the neritic carbonates from the Norwegian waters (Mortensen et al. 1995; Freiwald et al. 1997) they challenge the widely accepted idea of carbonate being mainly accumulated in the lower latitudes.

With the state of previous investigation outlined, one of the goals of this work is to estimate carbonate accumulation-rates and furthermore to establish a carbonate budget for a specific carbonate mound – the Propeller Mound (chapter 2). By setting up the stratigraphic framework for the budget calculation, it became evident that the sedimentary record on the mound is not linear but interrupted by several hiatuses. These observations lead to general questions regarding the sedimentary processes active on carbonate mounds. To target these questions a multy-proxy approach has been chosen to unravel the complex pattern for on-mound sedimentation and sediment preservation (chapter 3). Finally, the results of chapter 3 are linked to environmental conditions reconstructed from detailed paleontological observations (chapter 4). In particular, benthic foraminifera have been used to estimate shifts in the energy regime and water mass properties as well as in sediment supply, nutrification and coral growth.

1.2 CARBONATE MOUNDS

The focus of this study, Propeller Mound, does not fit the classic model of carbonate mounds. These are defined as being simple build-ups of carbonate mud containing sessile metazoa (e.g. Wilson 1975). The type of mound we refer to is an ecologically and morphologically highly complex structure better described by the modern approach of carbonate mounds being diverse complexes overlapping with ‘ecological’ reefs in composition, primary physical characteristics and diagenesis (Longman 1980; Pratt 1982; Wood 1999; Kopaska-Merkel and Haywick 2001; Wood 2001).

Carbonate mounds occur along the European Continental Margin in water depths between 1200 to 600m (Fig. 1.1) and include giant structures elevated up to several hundreds of metres above the seafloor (De Mol et al. 2002; Kenyon et al. 2003; van Weering et al. 2003). In shape they vary from singular conical structures to complex composite mounds. Linear mound-chains can be found as well as clusters of several isolated mounds (De Mol et al. 2002; van Rooij et al. 2003). In the Porcupine Seabight, where Propeller Mound is located, three mound provinces have been identified, each characterised by distinct morphological attributes. Intensive bottom sampling, video surveys and ROV observations have revealed that many of these mounds are covered by extensive thickets of cold-water corals (Freiwald and Shipboard scientific crew 2002; Olu and Shipboard scientific crew 2002).

A schematic model for the ontogeny of the giant carbonate mounds (Fig. 1.2) is given in Henriet et al. (2002) suggesting four stages of mound development. Beginning with a **trigger stage** (1), this would imply the prime building of a solid substratum as a base for settlement of coral larvae, sponges or other metazoa. During the following **booster stage** (2), in which metazoa settle on the previously formed hard grounds, the mound is in a phase of fast lateral and vertical extension. In the **coral bank stage** (3) the benthic fauna is dominated by colonizing filter feeders (corals etc.) and spatial habitat zonation is controlled by the

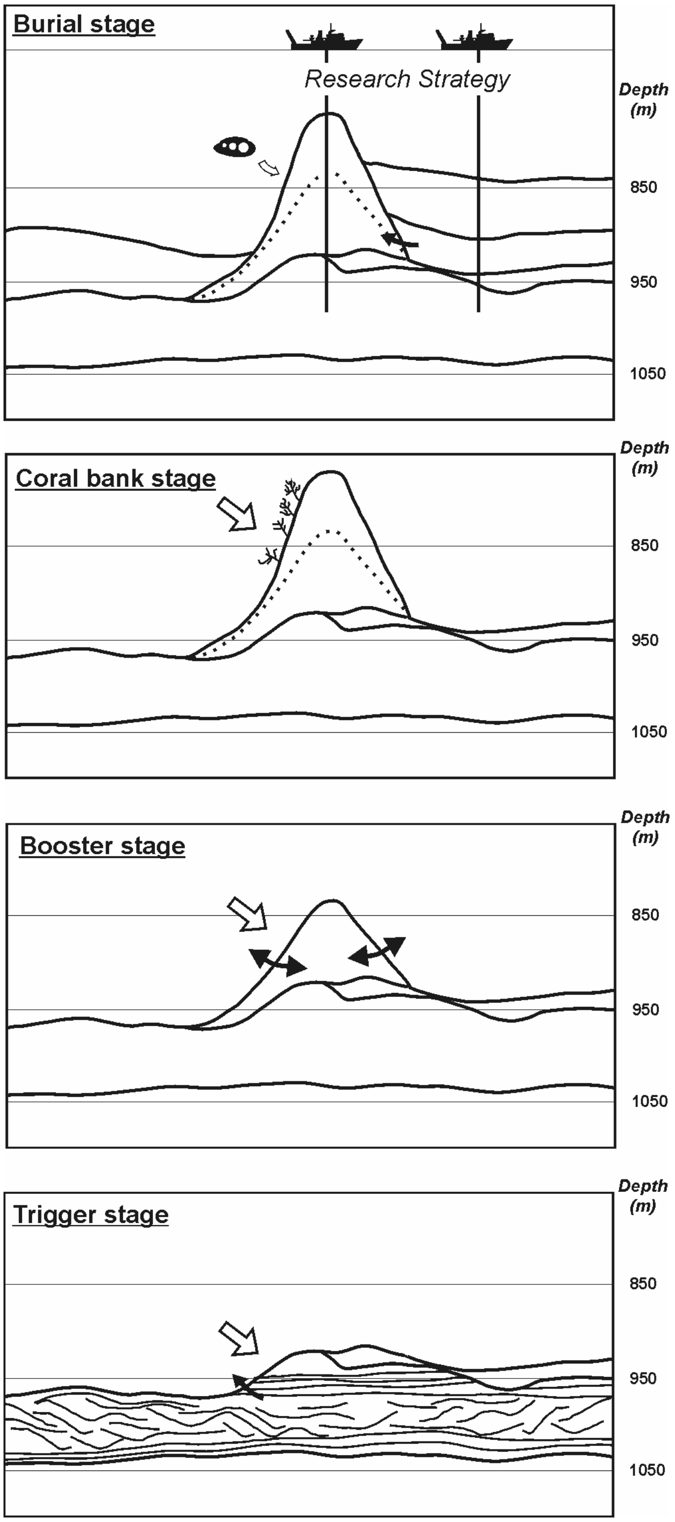

Fig. 1.2 Development model of a carbonate mound from Henriet et al. (2002). A trigger stage, in which hydrocarbon seepage may have occurred, is followed by the booster stage, a period of fast lateral and vertical growth. During the coral bank stage a dense cover of corals develops with spatial zonation of habitats controlled by the mound morphology and prevailing currents. In the burial stage the mound cannot keep up with the background sedimentation and shrinks relative to the surrounding seafloor.

morphology in interaction with strong currents. In the final **burial stage** (4) biota on the mound decrease and the mound growth cannot keep up with the background sedimentation. The mound declines and becomes buried under background sediments.

1.2.1 Corals

The two species *Lophelia pertusa* and *Madrepora oculata* are most common and are important framework builders and sediment bafflers. Highest densities of living coral are reported from mound tops and the upper flanks (Mortensen et al. 1995; Freiwald 2002).

From the general distribution pattern of *Lophelia pertusa* and *Madrepora oculata* it can be said that these corals are cosmopolitan species which can be found wherever conditions are favourable. In particular the water temperature needs to be between 4 to 12°C and a hard substrate must be available for colonisation (Rogers 1999). In addition, it is necessary for food to be available in sufficient quantities either through higher primary production in the surface waters or by redistribution of suspended particles in the bottom mixed layer (Frederiksen et al. 1992). In the Northeast Atlantic these corals preferentially grow in high-current areas with enhanced turbulence such as ridges and crests (Freiwald et al. 1997) or the up-current ends and tops of lithoherms, where streamlines are compressed (Messing et al. 1990), ensuring sufficient input of organic particles for the filter-feeders. Internal tides are also under discussion to determine their effect on the abundance of corals. Coral distribution appears to be related to areas where the seabed slope exceeds the critical value for internal tides and where enhanced near bottom tidal currents are present (Frederiksen et al. 1992).

Another critical issue for the corals in the Porcupine Seabight is the Mediterranean Outflow Water (MOW). Characterised by a salinity maximum (Rice et al. 1991), the MOW appears to be crucial for the thriving of *Lophelia* and *Madrepora*, as all *Lophelia* or *Lophelia*-dominated build-ups in the Porcupine Seabight appear within the MOW (Freiwald 2002). Up until now, it has not been determined if the MOW itself supports the corals or if it creates a pycnocline, at which organic particles are concentrated. Thus, the presence of MOW would increase the amount of food available for filter feeding in organisms such as corals. The influence of the MOW on carbonate mounds is discussed in more detail in chapter 3

1.3 REGIONAL SETTING

As mentioned in the previous sections, giant carbonate mounds occur in the Porcupine Seabight ~200km southwest off Ireland. There mounds are not randomly distributed but are grouped in the three provinces called the Belgica, Hovland and Magellan Mound Provinces respectively (Fig. 1.3). Each province is characterised by distinct features pertaining to shape, processes and development of the mounds, thus making the relatively small, enclosed area of the Porcupine Seabight a key location for carbonate mound studies.

The Porcupine Seabight itself is a tongue shaped embayment between the Porcupine Bank and the Irish Shelf. It is approximately 150km long and 65km wide, with water depths increasing from 250m in the north to 1700m in the south (Fig. 1.3). Underlying the Porcupine Seabight is the Porcupine basin, a basinal structure bordered on three sides by shallow basement platforms. The Porcupine Bank is the westernmost limit of the basin; the Slyne Ridge borders it to the north and the Irish mainland shelf to the east. The southern end is marked by the Goban Spur (Moore 1992). In the southwest, the basin opens into the Porcupine Abyssal Plain where water depths increase to more than 3000m.

The development of the Porcupine Basin began in the Middle to Late Jurassic as a failed rift of the proto-North Atlantic (Shannon 1991). Since initial rifting it has known a long history of extension associated with faulting and basin fill (Masson and Miles 1986; McCann et al. 1995). Up to 10 km of Mesozoic and Cenozoic sequences have been deposited in the basin. Supporting the earlier mentioned hypothesis of Hovland et al. (1994), the Porcupine Seabight was an area of active hydrocarbon generation with hydrocarbons proven by 4 significant discoveries in Jurassic and Cretaceous rocks (Croker and Shannon 1987) where oil has been found in test wells (Croker and Shannon 1995; Spencer and MacTiernan 2001).

1.3.1 Sedimentary inventory of the Porcupine Seabight

Present day sedimentation in the Porcupine Seabight is characterised by pelagic to hemipelagic sediment deposition, with the dominant sediment supply from the Irish and Celtic shelf and lesser input from the Porcupine Bank (Rice et al. 1991). In addition to the hemipelagic sediments, glacial Ice Rafted Debris (IRD) is present over the whole area of the Porcupine Seabight (Rice et al. 1991; Huvenne et al. 2002).

Strong contour following slope currents form extended drift deposits (van Rooij et al. 2003) while channel-and-levee complexes represent downslope sediment transport (Kenyon et al. 1978). The most developed channel system is that of the Gollum Channel which can be found at the slope and basin floor of the southern Porcupine Seabight. It forms the downstream component of a large fluvial system which extended onto the southern Irish shelf during sea level low stands (Tudhope and Scoffin 1995). Additionally, minor channels can be found further north on the eastern slope of the Porcupine Seabight. These may have been the submarine extension of glacial rivers crossing the exposed western Irish shelf during glacial periods and are most likely not active today (Wheeler et al. 1998).

Iceberg plough marks can be found down to a maximum of 500m water depth in the Porcupine Seabight and are deepest on Porcupine Bank where they occur between 140 and 500m. On the northern slope of the Porcupine Seabight plough marks can be found down to 300m (Belderson et al. 1973).

1.4 HYDROGRAPHY

Water masses affecting the carbonate mounds in the Porcupine Seabight are primarily Eastern North Atlantic Water (ENAW) and MOW. ENAW can be found below a seasonal thermocline (at ~50m) down to approximately 750m and is characterised by relatively warm and saline water (Hargreaves 1984; White and Bowyer 1997) originating in the Bay of Biscay (Ellet and Martin 1973; Pollard et al. 1996). It is underlain by MOW that occupies the whole Porcupine Basin between 800 to 1000m water depth (White submitted). MOW can be easily detected by its high salinity and low oxygen concentrations (Mohn 2000; White submitted) and appears to play a crucial role for the carbonate mounds in the Porcupine Seabight (Freiwald 2002). A permanent thermocline is formed between these two water masses where temperature drops from 10° to 4°C (Rice et al. 1991).

The dominant current affecting the mounds in the Porcupine Seabight is fed by the contour following branch of the northward flowing MOW. By entering the Porcupine Seabight it turns cyclonically with poleward flow along the Irish shelf at the eastern seabight margin (Pingree and LeCann 1989; Pingree and LeCann 1990). The component of this gyre too deep to bypass the Porcupine Bank, is reflected in the northern Porcupine Seabight, flowing south in the vicinity of the Hovland Mound Province (White submitted).

These general current patterns are superimposed by local dynamic processes such as internal tides, trapped waves or periodic barotrophic flows (e.g. Huthnance 1986; Rice et al. 1991; White 2001; White submitted). These become even more complex in the mound provinces as the rough topography generated by the mounds induces the localised strong currents and mixing that is essential for the corals to flourish (Freiwald 2002; White submitted). The locally intensified currents also create bottom nepheloid layers, commonly observed in the Porcupine Seabight (Rice et al. 1991).

Only limited information exists in the literature on hydrography during glacial times and information on current-intensities is absent. During glacials MOW did not reach as far north as the Porcupine Seabight (White subm.). It was replaced by slow flowing Glacial North Atlantic Intermediate Water (GNAIW) (Manighetti and McCave 1995). Data presented in chapter 3 support the absence of MOW during glacials, reducing the energetic regime in the Porcupine Seabight, thus affecting coral growth and mound development.

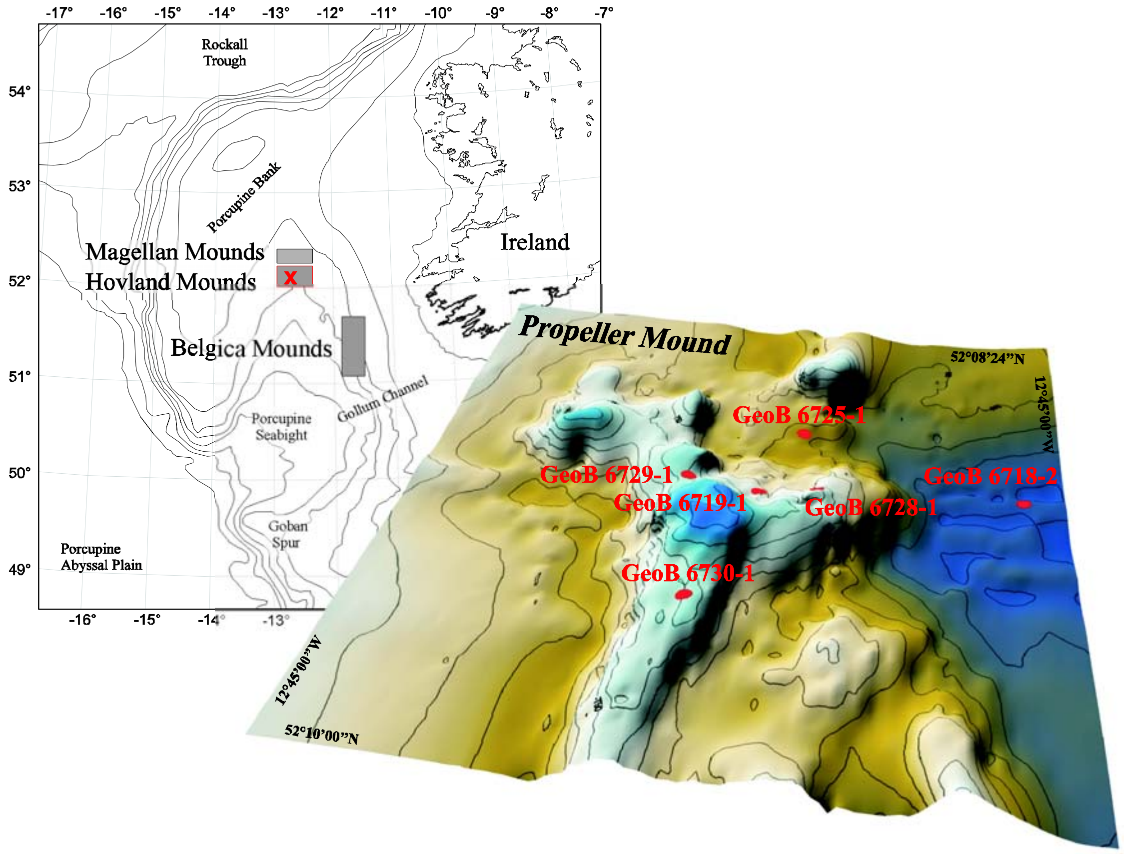

Fig. 1.3 Bathymetric overview of the Porcupine Seabight. Mound Provinces are indicated with rectangles. Detail map shows the Propeller Mound with coring locations for gravity cores (vertical exaggeration 2:1).

1.5 CARBONATE MOUNDS IN THE PORCUPINE SEABIGHT

Carbonate mounds in the Porcupine Seabight occur in three different mound provinces (Fig. 1.3), each with distinct characteristics (De Mol et al. 2002; Huvenne et al. 2002). Huvenne et al. (2003) and De Mol et al. (2002) describe the mounds in each province as having initiated more or less simultaneously, but it is still is under debate whether this occurred isochronically in all provinces. All mounds have an erosional surface as their base (De Mol et al. 2002) suggesting that oceanographic influences controlled mound initiation.

1.5.1 Belgica Mound Province

Located at the eastern slope of the Porcupine Seabight are the Belgica Mounds (Fig. 1.3), named after the Belgian research vessel R/V BELGICA. The Belgica Mound Province is composed of large mounds (up to 190m high) with their down slope flank well exposed and upslope flank almost entirely buried by hemipelagic sediments (Fig. 1.4). They are often arranged en echelon, which may indicate strong currents in the area (Wheeler et al. 1998; von Rooij et al. 2003), and are also associated with north-south trending channels. On some of the Belgica Mounds dense covers of cold water corals can be found (Olu and Shipboard scientific crew 2002; Thiede and Shipboard scientific crew in prep.), representing mounds in 'healthy' condition. According to the mound-development-scheme of Henriet et al. (2002), these mounds in are in the coral bank stage.

1.5.2 Magellan Mound Province

In evolutionary opposition to the Belgica Mounds are the Magellan Mounds located in the northern Porcupine Seabight (Fig. 1.3). They were discovered by the commercial survey ship SVITZER MAGELAN in Nov/Dec 1996. The Magellan Mound Province embraces several hundred small (<100m vertical diameter) mostly buried mounds, only recognisable on seismic profiles (Fig. 1.5). These mounds occur in a large variety of shapes (Henriet et al. 1998; De Mol et al. 2002; Huvenne et al. 2002) many of them associated with clear moat structures (Huvenne et al. 2002). Theses buried mounds represent the final stage as proposed by Henriet et al. (2002). Probably due to unfavourable living conditions, increased sedimentary input or changing oceanographic conditions these mounds were not able to keep up with the background sedimentation and were buried.

1.5.3 Hovland Mound Province

Located in the central Porcupine Seabight are the Hovland Mounds to which Propeller Mound belongs. They are located immediately south of the Magellan Mound Province and represent a possible link between the vital Belgica Mounds and already buried Magellan Mounds (Fig. 1.3).

The Hovland Mounds have been previously described by Martin Hovland et al. in 1994 on the basis of industrial seismic data. According to these about 31 separate carbonate knolls (here mounds) have been identified between 52° to 52°30'N and 12° to 13°W, grouped along two approximately N–S trending bathymetric lows. These two depressions are, probably formed by bottom current erosion or the escape of sediment pore water and gases (Hovland et al. 1994). The Hovland Mounds form large conical structures (1km across, 100m high) or elongated ridges (up to 5km long, 1km wide, 150m high) with associated deep moat structures (Hovland et al. 1994). Those moats are between 1 and 3km long and scoured out to depths of 20 to 150m. They occur on all sides of the mounds but are not necessarily symmetrical (Fig. 1.6) (De Mol et al. 2002).

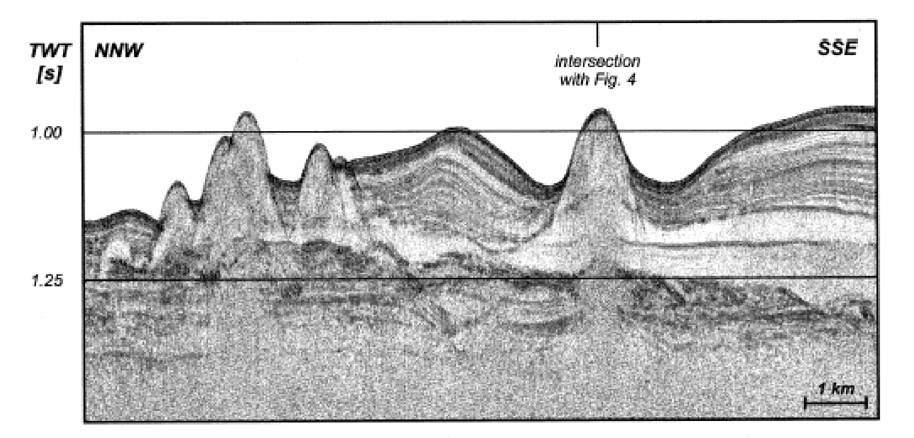

Fig. 1.4 Seismic profile through parts of the Belgica Mound Province (from van Rooij et al. 2003). The profile shows complex composite mounds in the north and a single mound in the southern part of the profile. Moats around the mounds are well developed and the embedding sequences are asymmetric at the composite mounds.

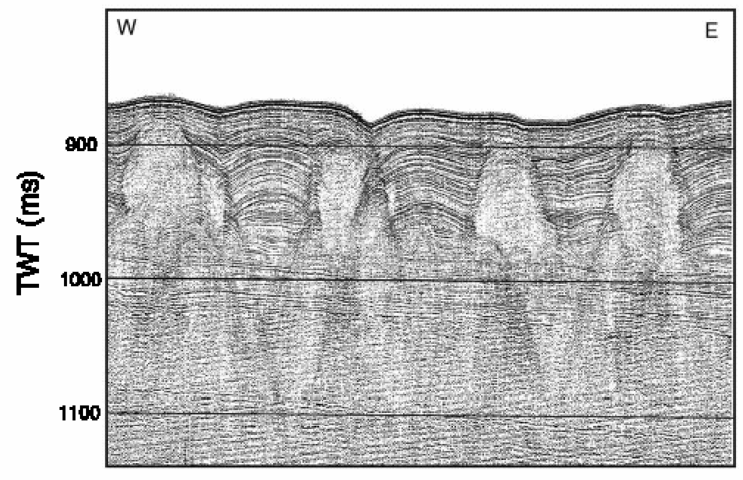

Fig 1.5 Seismic profile across the Magellan Mound Province (from Huvenne et al. 2003). Four buried mounds can be distinguished surrounded by moats. Tails underneath the mounds are diffraction effects.

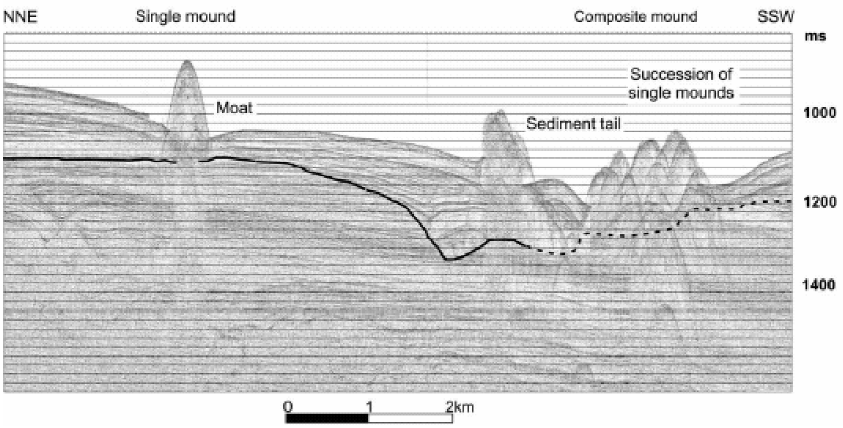

Fig 1.6 Seismic profile through the Hovland Mound Province (from De Mol et al. 2002) with single and composite mounds, associated moats and asymmetric sediment deposits.

The bases of the Hovland Mounds, as for many other mounds in the Porcupine Seabight, sit on an erosional surface that represents the youngest boundary of a complex cut-and-fill system (Fig. 1.6) (Hovland et al. 1994; De Mol et al. 2002). Interpreted from bore-hole data, this surface is expected to be of Early Pliocene age (Huvenne et al. 2003). During their later development the mounds have been embedded in sub-parallel to parallel seismic facies with continuous reflections of varying amplitude (De Mol et al. 2002).

The biological inventory of the Hovland Mounds is, like in other mound provinces, dominated by cold water corals. Video surveys revealed that as opposed to the Belgica Mounds, only small coral thickets occur here, mainly at the upper mound slopes and separated by extended areas of coral rouble (Freiwald and Shipboard scientific crew 2002; Olu and Shipboard scientific crew 2002).

1.6 PROPELLER MOUND

Propeller Mound (52°09'N / 012°46'W) is a roughly NS elongated trilobate structure rising 140m above the surrounding seafloor with ca. 2km latitudinal and 0.7km longitudinal extension (Fig. 1.3). Its three lobes point towards NNW, NE and S giving the mound a more or less propeller-like shape. Medium sized mounds are located ca. 0.3km northwest and ca. 1.2km north of Propeller Mound. Additionally, three small mounds are associated ca. 1.5km to the southeast.

As a submarine feature Propeller Mound has surprisingly steep slopes, with inclinations up to 45°. Steepest angles occur at the upper slope in the east and in the west. The northern slope declines with a maximum of 35°. Southern slopes have lowest inclinations with values hardly exceeding 10°. Those rather steep angles may be considered as evidence for the stabilising potential of the coral skeletons.

Propeller Mound is characterised by a distinct zonation in thickets of living corals, coral rubble facies and a dropstone pavement at its base. Hemipelagic sediments represent background conditions (Fig. 1.7).

At the summit area of Propeller Mound, coral rubble facies prevail. As indicated by box cores (Fig. 1.7 GeoB 6717-1 and 6708-2), the sediment consists of dead coral material in a matrix of sandy silty clay with very few small specimens of living corals. Coral fragments in these sediments range in size from a few millimetres to several decimetres and show stages of preservation from well preserved to obviously dissolved. At the upper flank the coral rubble facies intercepts patches of living corals, dominated by *L. pertusa* but with *M. occulata* also common (Fig. 1.7 GeoB 6720-1 and 6722-1). The sedimentary matrix at the upper slope is comparable to the matrix found at the mound top. Towards the base, these coral thickets are

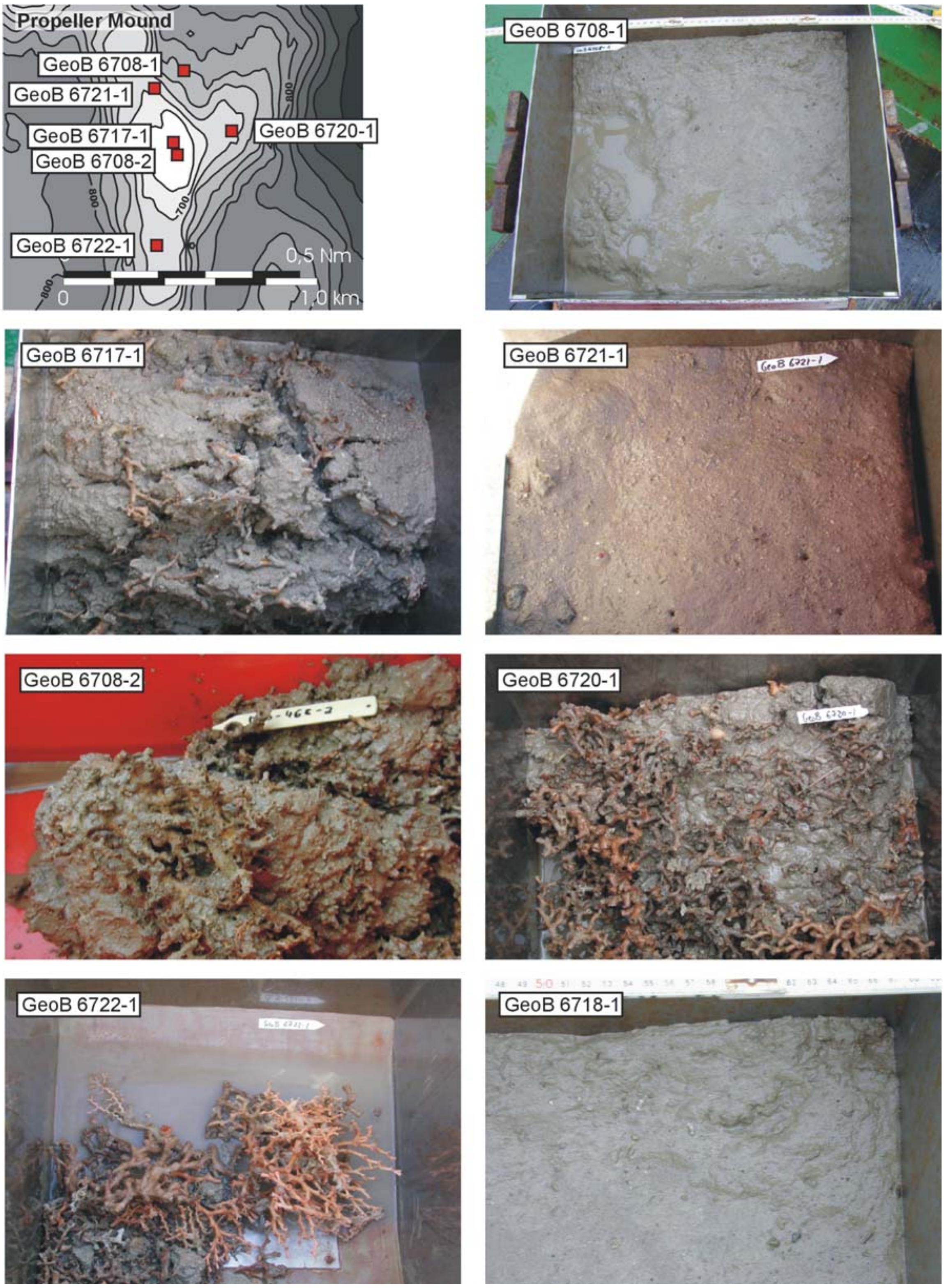

Fig. 1.7 Surface sediments from Propeller Mound and adjacent areas. Cores GeoB 6708-2 and 6717-1 represent the coral rubble facies from the summit areas of the mound with hardly any living corals. Living corals occur in core GeoB 6720-1 and 6722-1 from the spurs of the mound. GeoB 6708-1 and 6721-1 represent modified background sediment on-lapping the mound with drop stones exposed on the sediment surface. An example for the hemipelagic background sedimentation is given in core GeoB 6718-1, where sediments are unaffected by Propeller Mound.

again interspersed throughout a coral rubble facies, comparable to the top-mound sequences (Freiwald and Shipboard scientific crew 2002). In the north of Propeller Mound at the locations GeoB 6708-1 and 6721-1, slope sediments have been cored that consist of mainly sandy silty clay with silty sand in the top 5cm. In those cores drop stones have been found lying on the sediment surface. Towards the base of the mound drop stones become more and more abundant on the seafloor (Freiwald and Shipboard scientific crew 2002). In moats scoured out around the mound to the east and in the west, a well developed dropstone pavement covers the seafloor (Freiwald and Shipboard scientific crew 2002). Hemi-pelagic sediments cover the areas unaffected by the mound (Fig. 1.7 GeoB 6718-1). The tops of the smaller associated mounds are also covered with thickets of living corals.

1.7 MATERIALS AND METHODS

This thesis is based on the analysis of six gravity cores (table 1.1) collected from Propeller Mound and the adjacent areas during a campaign in September/October 2000 with the German research vessel POSEIDON (cruise POS 265 Freiwald and Shipboard scientific crew 2002). All gravity cores were retrieved within a radius of less than 1.5km (Fig. 1.3) and range in length from 350 to 600cm. The cores GeoB 6718-2, GeoB 6719-1 and GeoB 6725-1, collected from locations adjacent to Propeller Mound, contain mostly hemipelagic background sediments and will be further referred to as off-mound cores. The cores GeoB 6728-1, GeoB 6729-1 and GeoB 6730-1 will be referred to as on-mound cores. They have been retrieved from the upper areas of Propeller Mound and contain significant amounts of coral fragments embedded in a fine grained matrix. All cores were stored at 4°C for further treatment and finally archived in Bremen.

An overview of all methods applied to the sediment cores is given in table 1.2, but only those of which data are published, will be described in more detail. All published data acquired from the cores are accessible in the PANGEA database (http//pangea.de).

The corals themselves are the most prevalent feature of the on-mound sediments (Fig 2.2). Branches of the ahermatypic cold water corals *Lophelia pertusa* and *Madrepora oculata* build a loose framework, thus stabilising the mainly silty sediment matrix among the corals. In the on-mound sediments fragments of these two species (up to 30cm long) have been found. Although the coral density in the cores varies (see chapter 2), they are present at all depths throughout the cores. The state of preservation of the larger coral segments ranges from living coral at the core top to heavily dissolved and bioeroded fragments in the deeper parts. Besides the corals, the sediments also contain numerous echinoid fragments, bivalves, brachiopods, and gastropods. In the finer fraction foraminifera and sponge spiculae are common. The matrix itself consists of fine reworked coral material, coccoliths and terrigenious input.

In contrast to the on-mound cores, the off-mound sediments lack large coral components and consist of mainly hemipelagic sequences. Glacial sediments in these cores contain numerous drop stones embedded in sandy silty clays. Silty sands represent the interglacial sediments and mainly contain foraminiferal tests and lithic particles. Small coral fragments occur at the glacial – interglacial interface. Nevertheless the off mound cores are of particular value to the work as they represent the background conditions to which the on-mound cores can be compared.

All gravity cores were divided into one meter sections which were further split into working and archive halves. Their surfaces were cleaned, described and the colour of the sediments was scanned with a spectral photometer (Minolta CM 202) in the wavelength range of 400 to 700nm (visible light). Data resolution was 1cm. Finally cores and samples were stored at 4°C at the Department of Geosciences at Bremen University (GeoB).

The off-mound cores were prepared following the standard opening and cleaning procedure used at the GeoB. Due to their high coral content, conventional procedures for core treatment, sampling and analysis failed on the on-mound cores. The method used successfully on these coral bearing sediments is described in full detail below.

Because of their inhomogenity, on-mound cores containing corals cannot be opened immediately. Splitting the cores using standard methods would displace the corals, thus disturbing the sediment matrix and the associated sedimentary features. To preserve those features and their structure the on-mound cores were first frozen at –18°C for at least 72 hours. The frozen cores were split using a diamond bladed circular saw. Immediately after cutting, frozen cutting fluid and the upper surface of the cores were removed with a spatula or knife. To retain a good surface it was essential that the sediments were still frozen during the cleaning procedure.

Proceeding in this manner maintained the components in place and provided an intact surface for further scanning analyses. Serious damage to sedimentary structures due to freezing had not been observed with, even fragile features preserved.

1.7.1 Discrete samples

The working halves of the gravity cores were sampled with $10cm^3$ syringes at 5cm intervals. All collected sub-samples were weighed freeze-dried (Fig. 1.8). From weight loss during freeze drying of known sediment volume, dry bulk density, porosity and water content were estimated. The correction for salt content in the dried samples was carried out following

Table 1.1 Overview of gravity cores used in this thesis

Core number	Latitude N	Longitude W	Water depth m	Recovery cm	Content	Remarks
GeoB 6718-2	52°09.379’	012°45.158’	900	450	hemipelagic sediments	off-mound
GeoB 6719-1	52°09.233’	012°46.127’	758	580	hemipelagic sediments	off-mound
GeoB 6725-1	52°09.520’	012°46.010’	820	450	hemipelagic sediments	off-mound
GeoB 6728-1	52°09.240’	012°45.920’	749	590	corals in fine grained matrix	on-mound
GeoB 6729-1	52°09.231’	012°45.380’	711	460	corals in fine grained matrix	on-mound
GeoB 6730-1	52°08.861’	012°46.282’	704	360	corals in fine grained matrix	on-mound

Table 1.2 Analyses carried out on discrete samples

Core number	Absolute datings		Stable isotopes		$CaCO_3$	C_{org}	N	Grain size	Carbonate free sand content	Paleontological Analyses	Integrated glacial sand samples
	AMS C^{14}	U/Th	$\delta^{18}O$	$\delta^{13}C$							
GeoB 6718-2			X	X	X	X	X	X	X		X
GeoB 6719-1	4		X	X	X		X			X	X
GeoB 6725-1	2		X	X	X	X	X			X	X
GeoB 6728-1		4	X	X	X		X				
GeoB 6729-1		4	X	X	X		X				
GeoB 6730-1	5	5	X	X	X	X	X		X	X	

Non-destructive analyses

Core number	Computer tomography	Colour scans	Magnetic susceptibility	χ-ray density	XRF-element intensities	Digital pictures	Optical analyses on coral content
GeoB 6718-2	X	X	X	X	X		
GeoB 6719-1	X	X	X	X	X		
GeoB 6725-1	X	X	X	X	X		
GeoB 6728-1	X	X	X	X	X	X	X
GeoB 6729-1	X	X	X	X	X	X	X
GeoB 6730-1	X	X	X	X	X	X	X

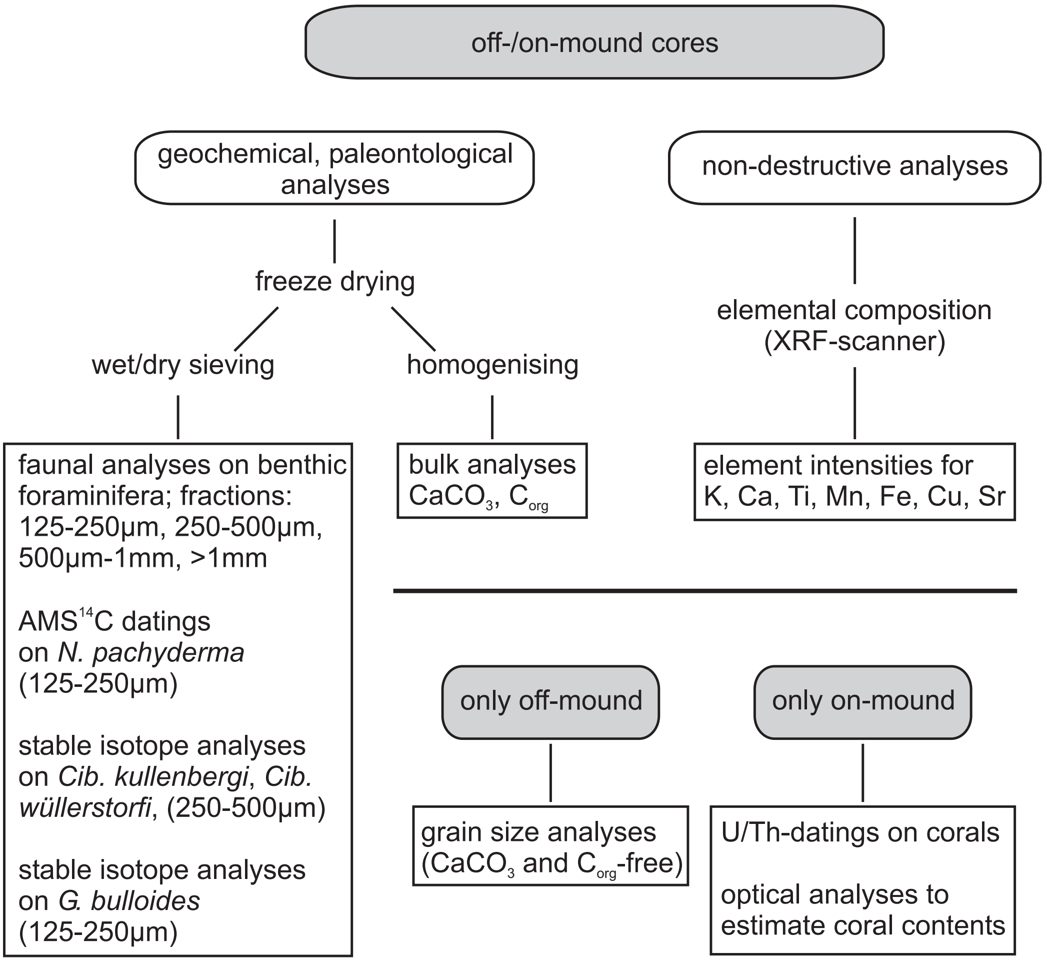

Fig. 1.8 Schematic flow chart of the methods applied for this study.

Weber et al. (1997), with an assumed density for the pore water of 1.024g/cm³. One set of samples was washed over 63 and 150µm mesh, dried and stored. For micro-paleontological analyses those were later dry sieved over 250, 500 and 1000µm meshes. Samples for bulk analyses were ground and homogenised using an agate mortar.

Stable Isotope analyses

Stable oxygen isotopes analyses were carried out on 3 to 5 individuals of the benthic foraminifera *Cibicides wuellerstorfi* or *Cibicides kullenbergi*, selected from the fraction 250 to 500µm. Isotopic composition of the foraminiferal tests was analysed on the CO_2 gas evolved by treatment with phosphoric acid at a constant temperature of 75°C. For all stable oxygen isotope measurements a working standard (Burgbrohl CO_2 gas) was used, which had been calibrated against PDB by using the NBS 18, 19 and 20 standards. Consequently, all

$\delta^{18}O$ data given here are relative to the PDB standard. Analytical standard deviation is about ±0.07‰ PDB (Isotope Lab Bremen University). Samples analysed parallel for *Cib. wuellerstorfi* and *Cib. kullenbergi* show comparable results for $\delta^{18}O$ for these two species. In addition to the benthic record, the top 1.5 meters of core GeoB 6725-1 were analysed for the stable oxygen isotope composition of planktic foraminifera. For these analyses 15 specimens of *Globigerina bulloides* were collected per sample.

Bulk sediment analyses

Homogenised samples were analysed for total carbon (C_{total}) and total organic carbon (C_{org}) as well as for total nitrogen content. Sample treatment and analyses were carried out at the GEOMAR in Kiel with a Carlo Erba NA-1500-CNS analyser following the standard procedure described in chapter 4. Carbonate contents of the sediments were finally calculated from the differences between C_{total} and C_{org} and expressed as calcite

$$CaCO_3 = (C_{total} - C_{org}) \times 8.33$$

Continuously analysed standards give a standard deviation of <2%.

Grain size analysis

Grain size spectra were measured with a Coulter Beckman Laser particle sizer LS 200 at the University of Bremen. The analyses were carried out on an organic carbon and carbonate free base at 10cm intervals. As preparation 10 ml H_2O_2 was added to 900–1500mg of sediment and topped up with water to ~80ml suspension. After 45min reaction time at ~75°C the samples were boiled for not more than 1 min to remove the H_2O_2. 10ml of 10% HCl was added to the samples, which were again boiled for 1min and filled with water to 800ml. After an at least 12 hour settling period the overlying fluid was decanted carefully. Finally the samples were boiled for 1 min with 300mg sodium-pyrophosphate and measured as soon as they had been cooled down to ambient temperature. The actual measurements were carried out in tap-water in which Ca^{2+} cations were replaced by Na^{+} cations, following the protocol used at the GeoB with run lengths of at least 120sec. The resulting detector-data were processed to grain size spectra using the Frauenhofer optical model. As standards 'glass pearls' ('std 1' <53µm, 'std 2' >53µm) were analysed and duplicate measurements were carried out at as least 1m intervals.

Micropaleontological analyses

All micro-paleontological analyses were carried out by Andres Rüggeberg at GEOMAR, Kiel. Detailed descriptions of the different approaches are given in chapter 4.

1.7.2 Non-destructive analyses

Non-destructive analyses such as scanning techniques (Fig. 1.8) provide rapidly accessible data at high resolution without consuming sample material. For correlation with already existing data the scanner data have been calibrated with discrete measurements (Fig. 2.3) where necessary and possible.

Element analyses

Elemental analyses on the investigated cores were performed by X-Ray Fluorescence (XRF) spectrometry. XRF detection units and the X-ray source were mounted on a mobile core scanning device located at the ODP Core Repository in Bremen (chapter 2).

This XRF Core Scanner is a non-destructive analysis system for scanning the surface of archive halves of sediment cores and has been developed and built at the Netherlands Institute for Sea Research (NIOZ), Texel, Netherlands (Jansen et al. 1998). Further detailed descriptions of the analysis procedure with the XRF-scanner in Bremen are given in Jansen et al. (1998) and Röhl and Abrams (2000). For this study the elements K, Ca, Ti, Mn, Fe, Cu and Sr were processed with the KEVEX^{Tm} software Toolbox ©.

Coral estimations

The high content of coral fragments in the on-mound cores is a challenge for analyses on discrete samples. Generally, particles in marine sediments are rather small so that they are more or less homogenously dispersed in each sample. If the sediments contain coral fragments, this assumption is no longer valid. These fragments can be so large that the sampling procedure influences the content of the sample as only small coral fragments and the sedimentary matrix can be sampled. Thus, for data interpretation it is essential to determine the amount of large coral fragments in the sediment independently as these have not been taken into account in the discrete samples.

A quantification of the corals in the on-mound core was done using optical analysis techniques on digital images from the core surfaces (for detailed description see chapter 2). In such images the contrast was increased and structural and median filter were applied to increase the differences between the corals and the sediment in which they are embedded. Finally the coral selection was carried out with a floating threshold to adjust the selection parameter to variations in the matrix. Finally the data were recorded as area percentage coral, which were for later comparison transformed into weight percentages assuming an average coral density of 2.66g/cm^3. The coral density for calibration was analysed with pychnometers on 15 different coral samples.

1.8 STRATIGRAPHY

Stratigrahy of the of the investigated sediment cores is based on AMS ^{14}C and U/Th ages as well as on δ^{18}O data analysed on the benthic foraminifers *Cibicides kullenbergi* and *Cibicides wuellerstorfi*. The stable oxygen isotope data were used for the correlation with the reference curve provided by Martinson et al. (1987) and also for inter-core correlation of the off-mound cores. A detailed description of the stratigraphic methods is given in chapter 2.

1.9 OVERVIEW OF OWN RESEARCH

The goal of this thesis is to contribute to the general understanding of carbonate mounds. For this reason geochemical, sedimentological and micro-paleontological analyses have been carried out to identify and if possible clarify processes active on these structures on the European margin. The results are presented and discussed in four manuscripts.

In the first manuscript

Carbonate budget of a cold-water coral carbonate mound:
Propeller Mound, Porcupine Seabight
B. Dorschel, D. Hebbeln, A. Rüggeberg, C. Dullo

a carbonate budget is established for Propeller Mound based on XRF-scanner Ca data, discrete $CaCO_3$ samples and information on the coral content in the sediments, interpreted in term with stratigraphic information.

To assess the coral contribution to the sediment, accumulation rates for coral fragments has been calculated and the amount of reworked coral material as part of the sediment matrix has been estimated. On average approximately ~30% of the carbonate found on-mound has been contributed by the corals. Accumulation rates for coral derived carbonate for the last 175kyrs varies between 0.017 and 0.391g/cm²kyr. Coral derived carbonate contributes to approximately 15% of the total carbonate accumulated on Propeller Mound. These carbonate accumulation rates are discussed with special regard to variations in the total carbonate accumulation between the on-mound and off-mound locations.

The second manuscript

Deglacial Sweeping of a Deep-Water Carbonate Mound

B. Dorschel, D. Hebbeln, A. Rüggeberg, C. Dullo, A. Freiwald

is devoted to sedimentary processes on Propeller Mound and especially to potential steering factors for sediment accumulation and sediment preservation. As the on-mound sedimentary record is fragmentary, the preserved intervals are characterised as glacial, interstadial and interglacial sequences on the basis of $\delta^{18}O$ data. This results in the interpretation that almost exclusively interstadial sediments have been preserved at the mound, with hiatuses related to glacial and interglacial intervals, highlighted by horizons enriched in coarse particles. Strong currents during interglacials, as indicated from grain size analyses from the off-mound location, are assumed to have removed unconsolidated glacial sediments from the mound by winnowing and further preventing interglacial sediments to be deposited. Additionally, observed erosion on the mound flanks may trigger mass wasting events.

In addition to the geochemical approaches in the first two manuscripts, micro-paleontological data identify environmental factors active on Propeller Mound.

Environmental changes and growth history of a cold-water carbonate mound (Propeller Mound, Porcupine Seabight)

A. Rüggeberg, C. Dullo, B. Dorschel, D. Hebbeln

Benthic foraminiferal assemblages identified for glacial and for interglacial periods in the areas adjacent to the mound provide information used to reconstruct the impact of changing oceanograpihc conditions. Peaks in *Elphidium excavatum*, typically found in shallow shelf areas (Seidenkrantz et al. 2000), indicate lateral advection of sediment to the mound area. For on-mound locations the foraminiferal assemblages support $\delta^{18}O$ data, indicating that almost no fully glacial or interglacial sediments have been preserved. A mound specific assemblage, dominated by epibenthic species, is discussed as a possible current indicator, closely related to intensity of MOW circulation in the area (chapters 4).

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CARBONATE BUDGET OF A COLD-WATER CORAL CARBONATE MOUND: PROPELLER MOUND, PORCUPINE SEABIGHT

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Abstract

High resolution studies from Propeller Mound, a cold water coral carbonate mound in the NE Atlantic, show that this mound consists to >50% of carbonate justifying the name ‘carbonate mound’. Through the last ~300kyrs approximately one third of the carbonate has been contributed by cold water corals, namely by the species *Lophelia pertusa* and *Madrepora oculata*. This coral-bound contribution to the carbonate budget of Propeller Mound is probably accompanied by an unknown portion of sediment buffered from suspension by the corals. However, extended hiatuses on Propeller Mound only allow the calculation of a net carbonate accumulation based on the preserved sediments. Thus, net carbonate accumulation for the last 175kyr accounts for only <0.3g/cm²*kyr, which is even less than for ‘normal’ off-mound sedimentation. These data imply that Propeller Mound faces burial by hemipelagic sediments as it has occurred to numerous buried carbonate mounds found slightly to the north of the investigated area.

2.1 INTRODUCTION

Cold water corals have been found all along the European margin from the Gulf of Cádiz south of Spain (Somoza et al. 2002) to northern Norway (Lindberg et. al. subm.). Often these are found on sea floor elevations called carbonate mounds (Freiwald 2002). On and around these structures, complex interactions of geological, biological and hydrological processes develop, with one of the key processes in the formation of these carbonate mounds being the growth of cold water corals, namely of the two common species *Lophelia pertusa* and *Madrepora oculata*. Such carbonate mounds are especially common along the Celtic margin in the Porcupine Seabight and in the Rockall region. There numerous types of carbonate mounds occur as single conical structures or as more complex composite mounds ranging in height above the sea floor from <1m to >150m, with a substantial part of the mounds being below the sea floor (De Mol et al. 2002; van Rooij et al. 2003). Thus, these carbonate mounds represent a significant volume within the sedimentary system of the Celtic margin.

As the growth rates of these aphotic cold water corals can be as high as 25mm/yr (Freiwald et al. 1997), comparable to those of reef forming corals in the oligotrophic shallow water reefs of the lower latitudes, the question arises to what extent the cold water corals and the carbonate mounds contribute to the global carbonate budget. Due to the volume of the carbonate mounds along the Celtic margin together with the neritic shallow water carbonates of the Norwegian margin (Mortensen et al. 1995; Freiwald et al. 1997), the common idea that calcium carbonate is mainly accumulated within the lower latitudes has already been challenged. The wide distribution of the cold water coral carbonate mounds has only recently being discovered and year by year new mound provinces are found (P. Croker pers. comm.). Therefore, up to now the carbonate stored in these mounds has not been considered in any global carbonate budget or any global model of the distribution of the greenhouse gas carbon dioxide.

To provide some background information about the carbonate budget of such carbonate mounds, a case study is presented here focusing on a particular mound: Propeller Mound (Fig 2.1). It is situated in the Porcupine Seabight, where three distinct mound provinces exist, each consisting of numerous carbonate mounds. The densest coral cover has been observed on mounds in the Belgica Mound province on the eastern side of the Porcupine Seabight. Less well developed coral thickets have been reported from the Hovland Mound province in the northern Porcupine Seabight. Slightly further to the north is the Magellan

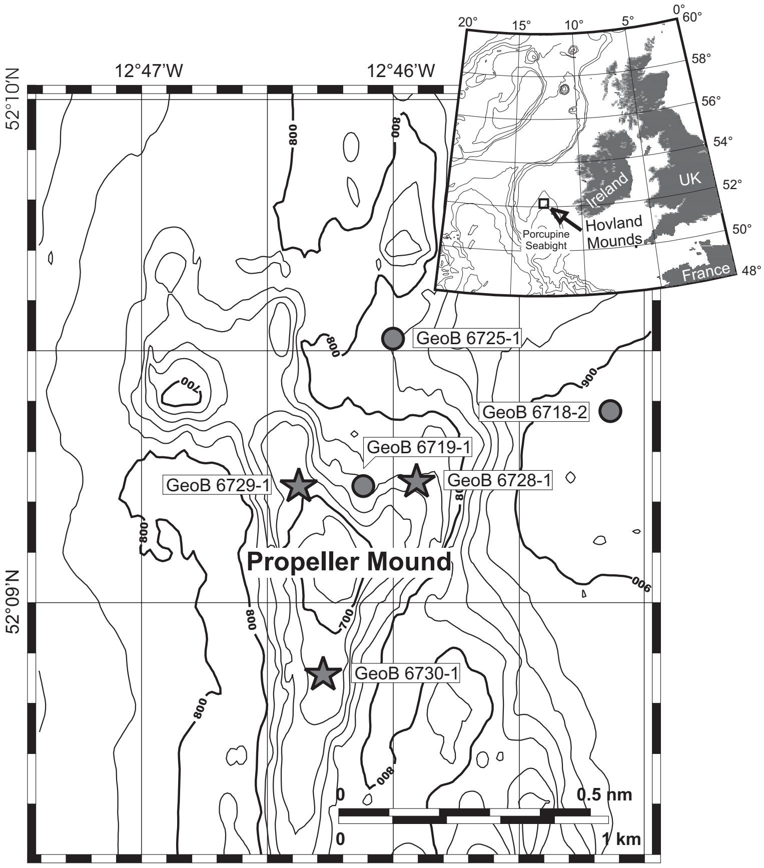


Fig. 2.1 Overview and morphological setting of the coring sites in the Propeller Mound area, Hovland Mound province, Porcupine Seabight. The stars indicate the on-mound cores, while the dots show the off-mound cores.

Mound province, which largely consists of buried mounds only detectable by seismic observations (Henriet et al. 1998; De Mol et al. 2002).

Propeller Mound belongs to the Hovland Mound province, where the carbonate mounds are associated with moats, indicating strong bottom currents in the area (Hovland et al. 1994; De Mol et al. 2002). It is located in 850m water depth. Its trilobate structure extends ca. 2km in latitudinal and 0.7km in longitudinal direction. With a maximum elevation of 140m it is one of the bigger composite mounds. Box corer sampling and ROV observations reveal patchy *L. pertusa* dominated thickets covering the upper slopes of Propeller Mound, which gradually change into a coral rubble facies mixed with hemipelagic sediments towards the lower slopes (Freiwald et al. 2000; Freiwald 2002).

By comparing sediment records from Propeller Mound itself and from the surrounding 'normal' hemipelagic sediments the specific settings in terms of carbonate sedimentation for this carbonate mound were assessed. Due to the complex stratigraphic record of Propeller

Mound, marked by numerous hiatuses, a quantitative carbonate budget is restricted to a net budget with respect to the preserved sediments. However, differences in contemporaneous sedimentation between the two settings were only possibly in a qualitative way, showing that due to the corals sedimentation on the carbonate mounds is enhanced by >15–20%.

2.2 MATERIALS AND METHODS

This study focuses on six gravity cores from the Propeller Mound and the adjacent areas taken during a sampling campaign by the German RV POSEIDON in the NE Atlantic in September 2000 (Freiwald et al., 2000; Table 2.1). The coring locations in the vicinity of Propeller Mound were taken along a transect from 1.2km NE off Propeller Mound (core GeoB 6718-2), 0.9km N off the mound at the adjacent moat (core GeoB 6725-1) and at the lower slope of the mound between its two northerly lobes (core GeoB 6719-1) (Fig. 2.1). These cores are between 4 and 5m long and consisted mainly of hemipelagic sediments. In the following text these cores are termed the off-mound cores.

The cores GeoB 6728-1, GeoB 6729-1 and GeoB 6730-1 were recovered within a ~0.5km radius from the three different lobes of Propeller mound (Fig. 2.1). These on-mound cores are 3.4 to 6m long and contain coral fragments embedded in a fine grained matrix (Fig. 2.2). The coral fragments (up to 30cm in length) built a loose uncemented framework in these cores and occurred with changing concentrations at all depths, with some intervals distinctly enriched in corals. These cores were opened while frozen using a diamond bladed circular saw. Cutting fluid and the uppermost surface were removed immediately after

Table 2.1 Overview about the coring locations

Station #	latitude	Longitude	water depth (m)	Recovery (cm)
off-mound				
GeoB 6718-2	52°09,379N	12°45,158W	900	450
GeoB 6719-1	52°09,233N	12°46,127W	758	480
GeoB 6725-1	52°09,520N	12°46,010W	820	450
on-mound				
GeoB 6728-1	52°09,240N	12°45,920W	749	590
GeoB 6729-1	52°09,231N	12°46,380W	711	460
GeoB 6730-1	52°08,861N	12°46,282W	704	360

opening. This procedure preserved a maximum of sedimentary structures, kept the corals in place and provided an excellent surface of the split cores for further scanning analyses.

2.2.1 Carbonate analyses

Discrete samples for carbonate analyses were taken every five centimetre. Analyses were carried out with a CARLO ERBA Elemental Analyzer at the GEOMAR in Kiel following standard procedures (for details see chapter 4). The standard deviation for the data presented here is <2%.

2.2.2 XRF-measurements for high resolution Ca and Fe analyses

In addition to the discrete carbonate analyses carried out in five centimetres intervals, high resolution (1cm) calcium (Ca) determinations were done with the CORTEX-XRF scanner (Jansen et al. 1998) at the University of Bremen. It is a non-destructive analysis system for scanning the surface of split sediment cores. Its central sensor unit consists of a molybdenum X-ray source (3–50kV), a Peltier-cooled PSI detector (KEVEX^{TM}) with 125µm beryllium window and a multichannel analyser with a 20eV spectral resolution. The system configuration (X-ray tube energy, detector sensibility) at the University of Bremen allows the analyses of elements from K (atomic no.19) to Sr (atomic no. 38) (X-ray tube voltage: 20kV).

For this study element intensities for Ca were analysed in 1 cm intervals, with each measurement taken over an area of 1cm^2. To obtain statistically significant data 30 second count time was used with an X-ray current of 0.087mA. The acquired XRF spectrum for each measurement was processed by the KEVEX^{TM} software Toolbox©. Background subtraction, sum-peak and escape-peak correction, deconvolution, and peak integration were successively applied. The resulting data are element intensities in counts per second (cps) and are used as a proxy for the carbonate content.

2.2.3 Image analysis for the quantification of corals

As both methods for the determination of the carbonate content do not allow differentiating between the carbonate from corals and carbonate from other sources, an image analysis was carried out in order to quantify the coral content in the cores. The coral fragments are easily distinguished from the matrix of hemipelagic sediments as it is evident from Fig. 2.2. For the image analyses, calibrated digital pictures were taken from the coral bearing cores with the GEO-Tek colour scanner at the University of Bremen.

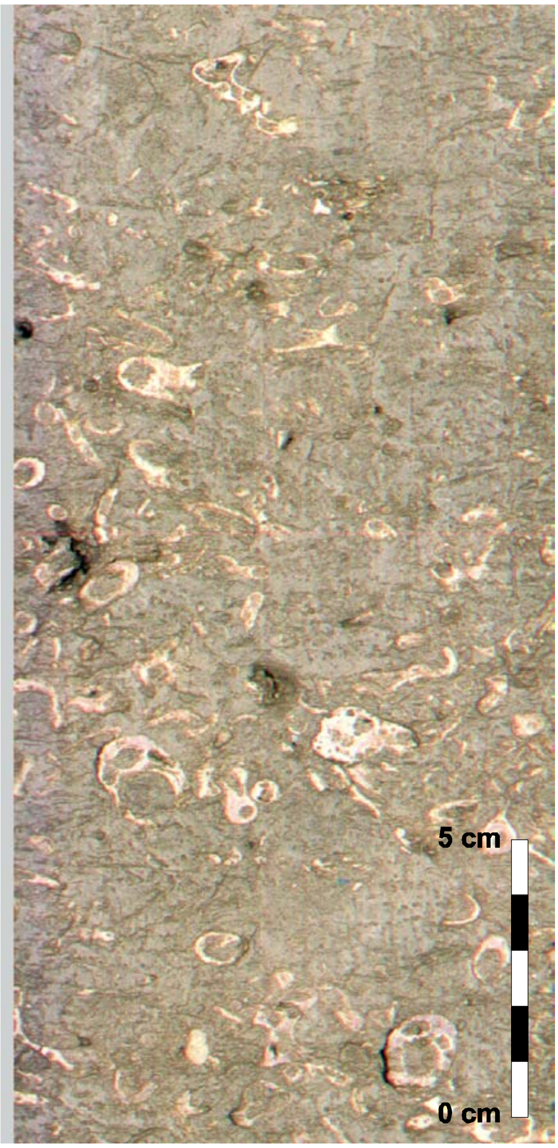


Fig. 2.2 Image showing coral fragments in the on-mound core GeoB 6730-1 (section 20-40cm).

The scans were transformed into grey-scale images (0 equals black, 250 equals white) and gridded with grid-intervals of one pixel. In a first step the grids were squared to increase the contrast. In the next steps a 7x7 pixel median filter and a 3x3 pixel structural filter were used on the images smoothing the background and eroding single pixels with a high contrast. After these preparations data were collected separately for every square centimetre over the full width of the split core. To detect the corals a threshold for each sampling interval, defined by the median grey value of the particular interval and an absolute offset of 20 units was used. The floating threshold was necessary to compensate for the variations in the matrix. In a last step the values were integrated over each centimetre depth interval resulting in area percentages of corals being present in each interval. Although this method did not differentiate between corals and e.g. molluscs or gastropods shells it still was sufficient due to the dominance of coral material relative to other carbonate particles.

For better comparison with the discrete and the XRF-scanner data sets the area percentages of the corals were transformed into weight percentages aragonite of the dry bulk sediment. The transformation was done using an average coral-density of 2.66g/cm³, according to density analyses carried out on 15 coral fragments from Propeller mound and an average dry bulk density (DBD) for the matrix of 1.19g/cm³.

2.2.4 Age determinations

The stratigraphic framework of the off-mound cores and partly also of the on-mound cores is based on AMS ^{14}C ages using mono-species samples (~10mg) of the planktic foraminiferal species *Neogloboquadrina pachyderma* (either dextral or sinistral) from the fraction 125–250µm (Table 2.2). The samples were analysed at the Leibniz Laboratory for Age Determinations and Isotope Research at the University of Kiel (Nadeau et al. 1997). The data were corrected for ^{13}C and the calibration to calendar years was done with the program Calib 4.3 (Stuiver and Reimer 1993) using the marine data set of (Stuiver et al. 1998), while ages greater 21 kyr BP were calibrated using the method of (Voelker et al. 1998) (Table 2.2).

Table 2.2 AMS ^{14}C dates of the cores GeoB 6719-1, GeoB 6725-1 and GeoB 6730-1

Laboratory number	core depth (cm)	^{14}C AMS age (yr BP)	+/– err. (yr)	calibrated age (cal yr BP)
Core GeoB 6719-1				
KIA 17091	18	6200	35	6640
KIA 17092	98	16100	70	18630
KIA 17093	163	21670	110	25420
KIA 17094	273	26780	180	30830
Core GeoB 6725-1				
KIA 16206	68	7135	45	7600
KIA 16202	168	20360	140	23530
Core GeoB 6730-1				
KIA 16201	23	4370	35	4500

In addition, fragments of the cold water coral *L. pertusa* have been taken from the on-mound cores and dated by the U/Th method using the Finnigan MAT 262 RPQ2+ Thermal Ionisation Mass Spectrometer (TIMS) at GEOMAR Kiel. Details of the cleaning procedure of these samples are given in Rüggeberg et al. (chapter 4). Data information is provided in Table 2.3.

2.3 RESULTS

In order to use the Ca intensities derived from the XRF scanning to increase the resolution of the carbonate content determinations, the XRF data have been correlated to the discrete carbonate content measurements for those core depths at which the latter are available. For the off-mound cores all data plot with r2 = 0.77 (Fig. 2.3a), disregarding the turbiditic samples at the base of cores GeoB 6719-1 and GeoB 6725-1 (see below). From the resulting linear regression the Ca intensities have been transformed to carbonate contents (Fig. 2.4). The same procedure has been employed for the on-mound cores. However, the relation ($r^2 = 0.59$) between Ca intensities and discrete carbonate measurements has a slightly lower slope (Fig. 2.3b), which is most likely due to a different composition of the cores induced by their coral content.

The carbonate contents in the off-mound cores are marked by high values (>30%) in the uppermost core sections (Fig. 2.4). Cores GeoB 6719-1 and GeoB 6725-1 also have comparable or even higher values at the base of the core. Below the maximum close to the core tops, all three cores have an extended core section with relatively low (<23%) carbonate content. However, in all three cores a significant double peak occurs in the middle of the low carbonate section (Fig. 2.4).

In the on-mound cores the carbonate contents are significantly higher than in the off-mound cores. They display some variation and range mostly between 30% and 70% and do not show any similarities neither to the off-mound cores nor to each other (Fig. 2.5). Among these cores the average carbonate content is relatively constant, ranging from 53% (GeoB 6730-1) to 56% (GeoB 6728-1) to finally 57% (GeoB 6729-1). The coral carbonate contents range between almost 0% and maximum values of ~40%, with the coral carbonate content in core GeoB 6730-1 (on average 17%) being almost three times at high as in the two other cores (on average 5%) (Fig. 2.6). There seems to be no significant correlation between total carbonate and coral carbonate contents.

Table 2.3 U/Th ages for the cores GeoB 6728-1; GeoB 6729-1 and GeoB 6730-1

	core depth (cm)	^{234}U/^{238}U (‰)	^{238}U (dpm/g)	^{230}Th (dpm/g)	^{232}Th (dpm/g)	^{230}Th/^{232}Th (dpm/g)	^{230}Th/^{234}Th (dpm/g)	age (kyr)	error (kyr)
Core GeoB 6728-1									
	3	86±2	2.251±0.002	1.825±0.008	0.01621±0.00002	112.6±0.5	0.741±0.003	**143**	1.3
	83	82±3	2.549±0.003	2.263±0.004	0.00533±0.00001	424.6±0.9	0.818±0.002	**178**	1.0
	218	72±2	2.495±0.003	2.323±0.009	0.01473±0.00003	157.7±0.7	0.865±0.004	**207**	2.6
	368	60±3	2.574±0.004	2.531±0.008	0.00929±0.00002	272.3±1.0	0.924±0.003	**261**	3.6
Core GeoB 6729-1									
	23	113±3	3.086±0.003	1.332±0.006	0.02022±0.00030	66.8±0.3	0.388±0.002	**53**	0.3
	73	80±3	2.416±0.003	2.095±0.007	0.01395±0.00002	151.0±0.5	0.802±0.003	**170**	1.4
	268	44±2	2.630±0.003	2.607±0.006	0.00678±0.00001	385.5±1.0	0.949±0.003	**300**	4.1
Core GeoB 6730-1									
	88	107±2	3.294±0.003	2.122±0.003	0.01370±0.00003	155.8±0.4	0.582±0.001	**93**	0.3
	158	109±4	1.994±0.003	1.526±0.006	0.03068±0.00004	50.6±0.2	0.690±0.003	**124**	1.0
	268	82±7	2.673±0.008	2.357±0.007	0.01040±0.00001	226.5±0.7	0.815±0.003	**176**	1.8
	358	62±3	3.184±0.005	2.891±0.011	0.02652±0.00004	109.9±0.5	0.855±0.004	**207**	2.5

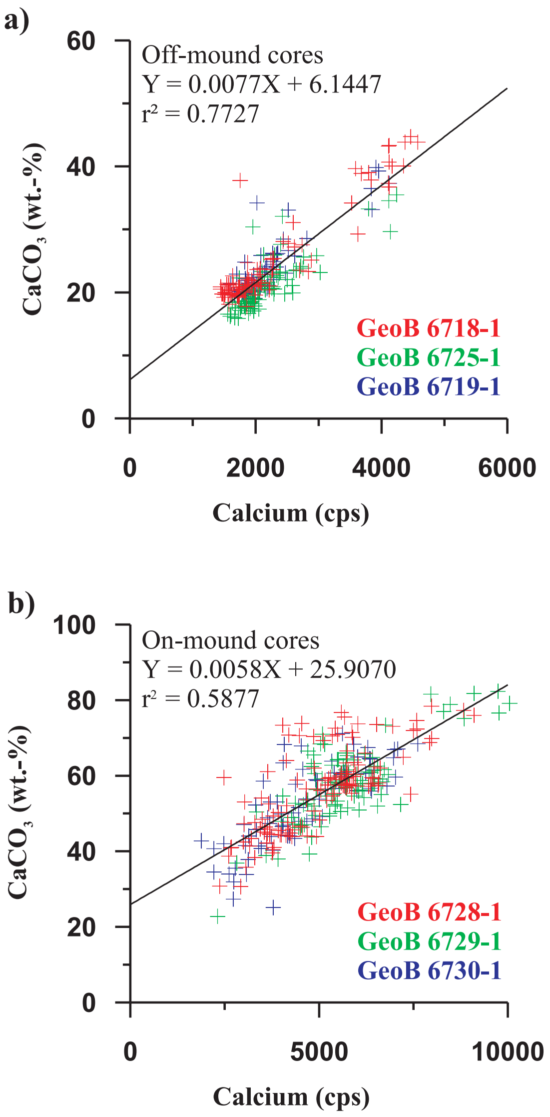
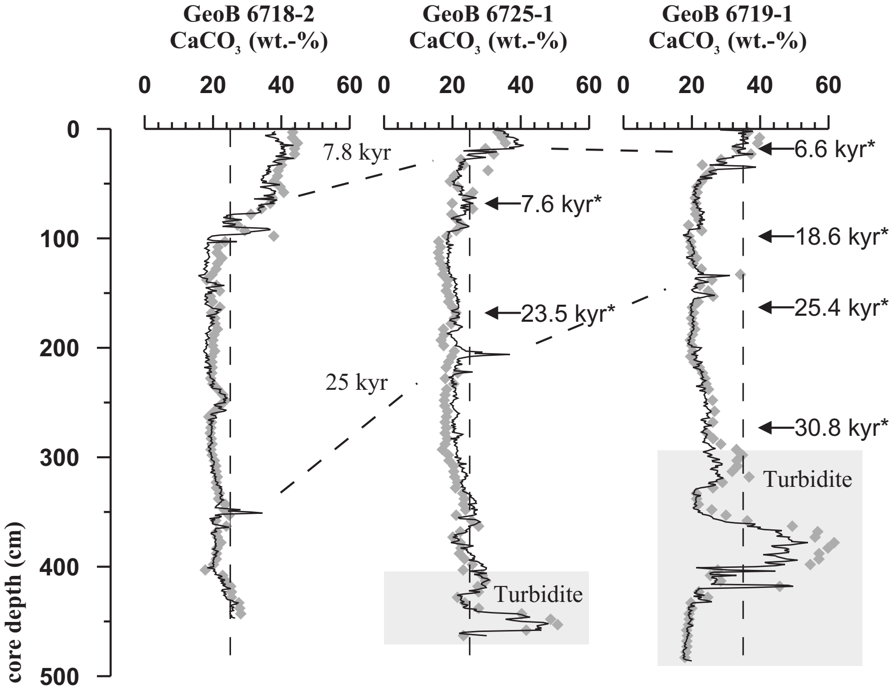


Fig. 2.3 Calcium carbonate content versus XRF Ca counts for (a) the off-mound cores GeoB 6718-2, GeoB 6725-1 and GeoB 6719-1 and (b) the on-mound cores GeoB 6728-1, GeoB 6729-1 and GeoB 6730-1. Regressions of (a) is based on all off-mound data excluding the turbidite sections in GeoB 6719-1 and GeoB 6725-1. Regression (b) is based on all on-mound data.

2.4 STRATIGRAPHY

According to the AMS ^{14}C ages the off-mound cores (GeoB 6718-2, GeoB 6719-1 and GeoB 6725-1) appear to contain quite continuous sediment records going back to ~30 cal. kyr BP (Fig. 2.4), which is also corroborated by δ^{18}O data (chapter 3 & 4). In cores GeoB 6719-1 and GeoB 6725-1 the AMS ^{14}C dates reveal a regular sequence with younger ages following older ones.

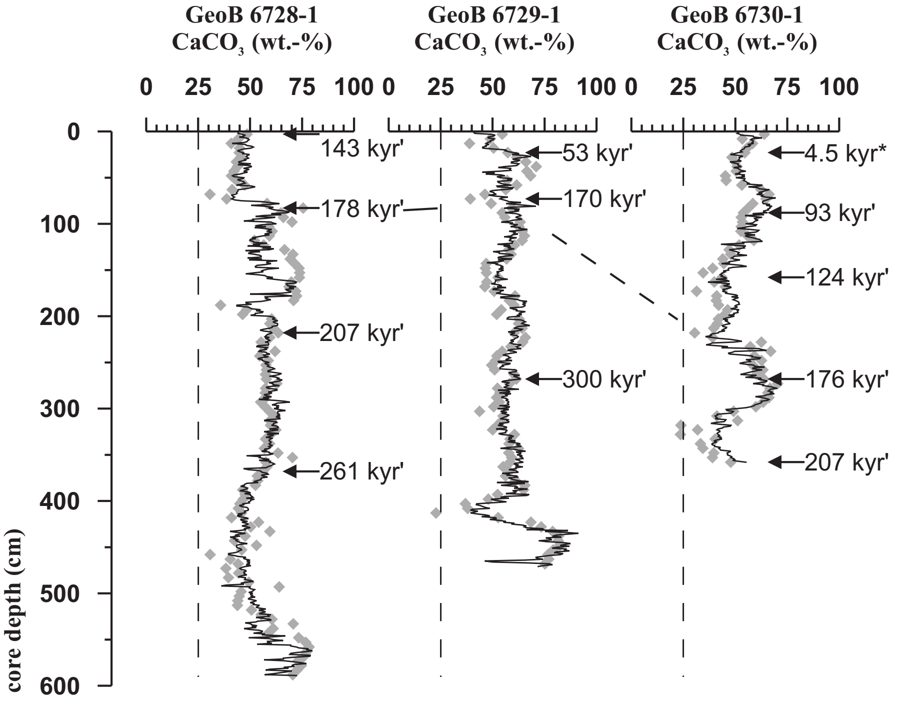


*AMS ^{14}C dates calibrated to calendar years

Fig. 2.4 $CaCO_3$ content versus depth in the off-mound cores based on calibrated scanner data (line) and discrete samples (rectangles). The turbidite sections are marked by the shaded area and stratigraphical information is provided by AMS ^{14}C dates. Correlation horizons for budget calculations are indicated by the dashed lines.

The records are marked by the same major turbiditic sequence occurring at the base of cores GeoB 6719-1 (below 294cm core depth) and GeoB 6725-1 (below 404cm core depth). According to the oldest AMS date in core GeoB 6719-1 just above the turbidite it seems to be slightly older than 31 cal. kyr BP. Due to higher sedimentation rates in core GeoB 6718-2 the turbidite level, if present, is not reached in this core.

Besides the AMS ^{14}C dates shown in Fig. 2.4 an additional stratigraphic tie point is indicated by a characteristic double peak in the carbonate records in all three cores (GeoB 6718-2: 364–551cm, GeoB 6719-1: 134–152cm and GeoB 6725-1: 206–222cm). Being situated between the AMS ^{14}C dates of 25.4 cal. kyr BP just below (GeoB 6719-1) and 23.6 cal kyr BP just above (GeoB 6725-1), the second and higher part of this carbonate double peak is assumed to be ~25 cal. kyr old. As it occurs in all three cores it provides a perfect correlation tie point for these cores. It is probably related to the Heinrich 2 event and its European precursor event, both dated to 25.6 respectively 24 cal. kyr BP (Grousset et al. 2000).



*AMS ^{14}C dates calibrated to calendar years
' U/Th ages

Fig. 2.5 CaCO3 content versus depth in the on-mound cores based on calibrated scanner data (line) and discrete samples (rectangles). Stratigraphical information is provided by AMS ^{14}C and U/Th dates. Correlation horizons for budget calculations are indicated by the dashed lines.

Another stratigraphical tie point for the correlation of these off-mound cores is the significant increase in the carbonate content close to the top of the cores (Fig. 2.4). It is interpreted to reflect the onset of the Holocene, when drastic paleo-environmental changes resulted in a distinct shift towards these higher carbonate contents. This interpretation is also supported by $\delta^{18}O$ measurements (chapter 3 and 4). Thus, the first sample in each of the cores at which the carbonate content began to remain at the Holocene level is set to an age of 7.8 cal. kyr BP, corresponding to this date, the standard oxygen isotope curve of Martinson et al. (1987) reaches a constant Holocene level. In addition, to allow a quantitative comparison of the cores it is assumed that the core tops reflect the present-day surface sediment.

In these cores the sedimentation rates are generally higher during the glacial period compared to the Holocene. The general trend of decreasing sedimentation rate toward Propeller Mound is assumed to be due to enhanced winnowing (chapter 3) related to focusing of bottom currents around the mound (Guo et al. 2000). Such a mechanism has been named as

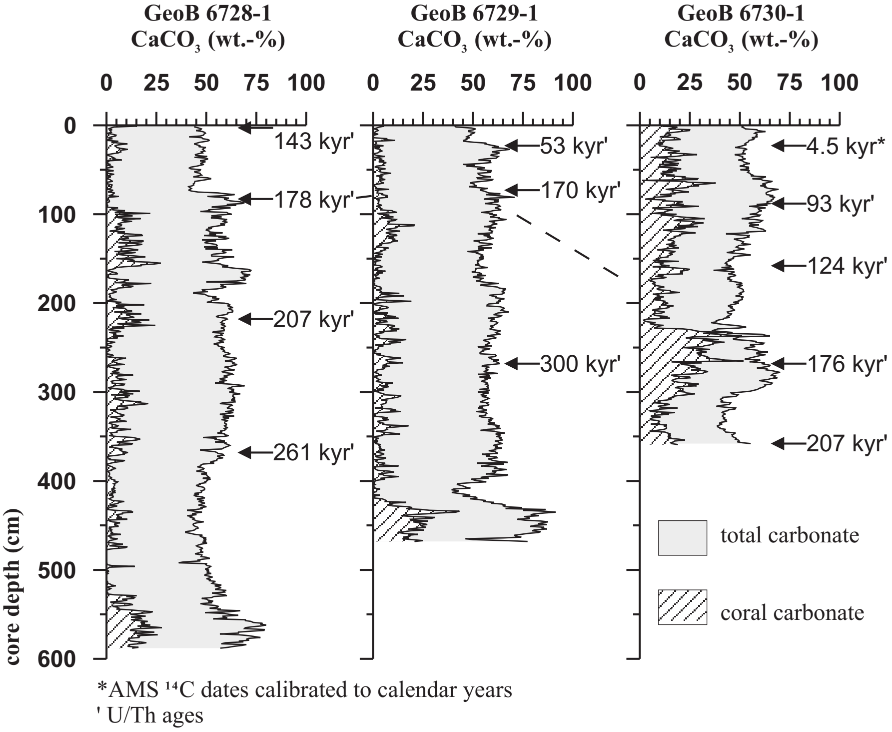


Fig. 2.6 Total $CaCO_3$ content and coral derived $CaCO_3$, derived from image analyses, versus depth in the on-mound cores. Stratigraphical information is provided by AMS ^{14}C and U/Th dates. Correlation horizons for budget calculations are indicated by the dashed lines.

the primary process generating the moats around most of the carbonate mounds in the Porcupine Seabight (De Mol et al. 2002).

According to AMS ^{14}C datings, U/Th measurements and $\delta^{18}O$ records, the on-mound cores (GeoB 6728-1, GeoB 6729-1 and GeoB 6730-1) are marked by numerous hiatuses with almost no fully interglacial or fully glacial sediments being preserved (chapter 3). Nevertheless, the available U/Th ages provide means by which the net carbonate accumulation (i.e. the preserved material) can be put into a temporal framework.

U/Th data with ages between 170 and 178kyr available for all three cores (Fig. 2.5) allow a correlation of the cores with respect to net sedimentation over a comparable time interval, i.e. the last ~175kyr, which covers core intervals of 83cm (GeoB 6729-1), 73cm (GeoB 6728-1) and 268cm (GeoB 6730-1). Older available U/Th dates in core GeoB 6728-1 and GeoB 6729-1 allow for the determination of net sedimentation even further back in time.

Of course, the sedimentation rates derived by this method do not reflect the actual sedimentation rate at Propeller Mound during these time intervals (chapter 3). However, the net sedimentation, which really contributes to the shape and size of the actual Propeller

Mound is well covered and allows a comparison with the surrounding drift sediments on a Late Pleistocene time scale. Thus, the core tops again have been set to a zero age, although it is clear, e.g. from core GeoB 6728-1 with an age of 143kyr close to the surface (Fig. 2.5), that this assumption is not valid in a solely stratigraphic sense. Nevertheless, for the calculation of net accumulation rates it appears to be the correct approach.

According to an AMS ^{14}C date of 4,500 cal. yrs BP (Fig. 2.5) and rather low δ18O data (chapter 3 & 4) core GeoB 6730-1 contains a section of Holocene sediments at its top. For a quantitative comparison with the off-mound cores it is tentatively assumed that the core section from 0 to 53cm in core GeoB 6730-1, marked by low $\delta^{18}O$ data, corresponds to the last 7.8kyr.

2.5 DISCUSSION

In order to discern the impact of a carbonate mound on carbonate sedimentation, the sedimentological data have to be put in a wider context which also includes "normal" hemipelagic sediments, i.e. not affected by a carbonate mound, to assess the background sedimentation, which of course also affects the carbonate mound. In this study the background sedimentation is reflected in the off-mound cores, which can be compared on various scales with the on-mound cores representing the carbonate mound setting.

2.5.1 Carbonate content

The off-mound cores can be clearly distinguished in Holocene (0–7.8 cal. kyr BP) and Last Glacial Maximum/Termination 1 (LGM-T1, 7.8–25 cal. kyr BP) sections, with the sediments of these two periods being quite different (Fig. 2.4). During the LGM-T1 the average carbonate content in the three cores ranges between 20 and 23 wt.-%, while during the Holocene much higher values of 34 to 37 wt.-% are observed (Table 2.4).

As is to be expected, the carbonate contents on the carbonate mound are significantly higher with values below 30 wt.-% relatively rare (Fig. 2.5). According to the available stratigraphic tie points, sediments of the last ~175kyr that have remained in place can be compared. They are marked by average carbonate contents between 48 and 54 wt.-% with slightly higher average values (~57 wt.-%) if the older sediments are also taken into account (Table 2.4). Only for core GeoB 6730-1, can average Holocene carbonate contents also be described. At 53 wt.-%, these are in line with the other "young" (i.e. <175kyr) on-mound sediments.

Comparing the two settings it appears that the carbonate contents of the on-mound sediments are on average >25 wt.-% higher than those of the Holocene off-mound sediments. If the low carbonate glacial off-mound sediments are considered, the difference is even greater. However, as no comparable glacial sediments are preserved on the mound (chapter 3) this comparison will focus on the Holocene off-mound sediments.

Table 2.4. Sediment composition and accumulation of the investigated sediment cores

	GeoB 6718-2		GeoB 6725-1		GeoB 6719-1	
	Holocene	Glacial	Holocene	Glacial	Holocene	Glacial
Time interval (kyr)	0–7.8	7.8–25	0–7.8	7.8–2 5	0–7.8	7.8–25
Depth interval (cm)	0–78	78–352	0–18	18–206	0–26	26–134
sed. rate (cm/kyr).	9.99	15.94	2.30	10.94	3.33	6.28
Mean DBD (g/cm^3)	1.19	1.06	1.31	1.17	1.29	1.17
Mean CaCO$_3$ (wt.-%)	37.17	20.41	37.24	21.61	34.44	22.50
Accumulation (g/cm^{2}kyr)						
Bulk sediment	11.887	16.856	3.022	12.756	4.283	7.355
CaCO$_3$	4.418	3.440	1.125	2.757	1.475	1.655

	GeoB 6728-1		GeoB 6729-1		GeoB 6730-1	
	last 175 kyr	Older	last 175 kyr	Older	Holocene	last 175 kyr
Time interval (kyr)	0–178	0–261	0–170	0–300	0–7.8	0–176
depth interval (cm)	0–83	0–368	0–73	0–268	0–53	0–268
sed. Rate (cm/kyr)	0.47	1.41	0.43	0.89	6.79	1.52
mean DBD (g/cm^3)	1.23	1.28	1.24	1.26	1.42	1.45
Mean CaCO$_{3\ (total)}$ (wt.-%)	48.08	56.24	54.09	57.34	53.56	52.93
Mean CaCO$_{3\ (coral)}$ (wt.-%)	2.92	6.13	3.07	4.71	15.62	17.69
Accumulation (g/cm^{2}kyr)						
bulk sediment	0.575	1.805	0.530	1.125	9.634	2.208
total CaCO$_3$	0.277	1.015	0.287	0.645	5.160	1.169
coral CaCO$_3$	0.017	0.111	0.016	0.053	1.505	0.391

2.5.2 Coral content

Despite some tiny coral fragments in the off-mound cores (chapter 4), significant amounts of corals have only been found in the three on-mound cores. According to the image analyses the coral content in the <175kyr section of cores GeoB 6728-1 and GeoB 6729-1 mainly ranges between 0 and <20 wt.-% and is on average rather low (3 wt.-%, Tab. 2.4). Further down core, the average coral content can be slightly higher (4-6 wt.-%). In contrast, in core GeoB 6730-1 the average coral content (17 wt.-%) as well as the individual data points (Fig. 2.6) are considerably higher.

Although the coral contents differ strongly, the carbonate contents are quite similar among the three on-mound cores. Subtracting the coral content from the carbonate content in core GeoB 6730-1 yields a background carbonate content of 35 wt.-%, which is very close to the carbonate content of the Holocene off-mound sediments. Thus, for this core it can be assumed that the carbonate in the sediment consists of the normal background sedimentation (~35 wt.-%) accompanied by ~17 wt.-% coral carbonate. In this case the coral fragments in the core must be relatively large assuring the detection of all coral particles by the image analysis.

Extending this observation to the other two on-mound cores reveals a different pattern. Assuming the background carbonate content (~35 wt.-%) to be comparable at all sites, these two sites have, in addition to a coral content of ~3 wt.-%, an undefined carbonate contribution of ~13 wt.-%. Together with the corals this adds up almost exactly to the coral content in core GeoB 6730-1. Thus, this 13 wt.-% of carbonate might also reflect a coral contribution. However, this coral material must be so fine grained that it is not detectable by image analysis.

While core GeoB 6730-1 is taken close to the top of Propeller Mound at a site of recent coral growth, indicated by living corals in an adjacent box core (GeoB 6722-1, Freiwald et al. 2000), no living corals have been reported from sites close to the other two cores. If core GeoB 6730-1 contains mainly corals grown at the site, these are most likely preserved in rather large pieces, which will be detected by the image analyses. If, in contrast, the corals found in the other two cores have been transported to the core sites from fields of active coral growth further upslope, the delicate coral fragments were probably subject to major destruction during the transport resulting in a shift of the coral material from the coarse into the fine fraction, i.e. out of the detection window of the image analysis.

Based on this assumption it appears that the coral content in the on-mound cores is rather constant between 15 and 20 wt.-%, adding to a background carbonate content of ~35 wt.-%, typical for the Holocene off-mound sediments.

2.5.3 Carbonate accumulation rates

Along the off-mound transect the sedimentation rates decrease significantly towards the mound from 10cm/kyr (Holocene) and 16cm/kyr (LGM-T1) to 3.3/6.3cm/kyr (Table 2.4), most likely due to winnowing induced by bottom currents focused around the mounds. Interestingly, sediment composition, with respect to carbonate content seems to be unaffected by this process. It also becomes clear that glacial sedimentation rates are significantly higher than those found in the Holocene (Table 2.4, Fig. 2.7).

In terms of total and carbonate accumulation rates, which have been calculated according to van Andel et al. (1975), a similar pattern of decreasing values towards the mound appears. For the comparison with the on-mound sediments only core GeoB 6718-2 will be considered as it is located furthest away from the mound. Being the least affected by any mound-induced bottom current disturbances, this core is probably the best representative of background sedimentation in the area. On a Holocene/LGM-T1 scale its total accumulation rate (AR_{total}) and its carbonate accumulation rate ($AR_{carbonate}$) range between 11.9/16.9g/cm^2*kyr and 4.4/3.4g/cm^2*kyr, respectively (Table 2.4, Fig. 2.7).

Over the rather long time periods represented in the on-mound cores the resulting sedimentation rates (<1.5cm/kyr), AR_{total} (<2.2g/cm^2*yr) and $AR_{carbonate}$ (<1.2g/cm^2*kyr) are low and partly only around 10% of the comparable off-mound values. This, of course, is due to the incompleteness of the records as mentioned above. Thus, these numbers are only net rates

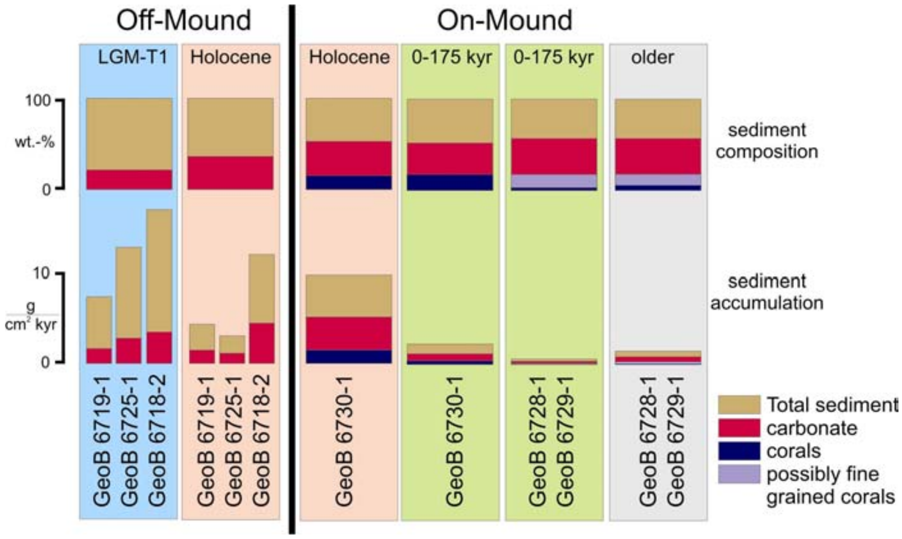


Fig. 2.7. Sediment composition and sediment accumulation in the Propeller Mound area indicated for the intervals Last Glacial Maximum-Termination 1 (LGM-T1), Holocene for the off-mound location and Holocene, the interval 0-175kyr and older sediments for the on-mound locations.

over the respective time spans but they do not allow a direct comparison with the off-mound cores in terms of real sedimentation.

The only direct comparison appears to be possible for the Holocene sections of the on-mound core GeoB 6730-1 and the off-mound core GeoB 6718-2, although the completeness of these sections in a stratigraphical sense can only be assumed. AR_{total} and $AR_{carbonate}$ are quite similar in both cores, with the AR_{total} being slightly higher in the off-mound core (11.9g/cm^2*kyr vs. 9.6g/cm^2*kyr) and $AR_{carbonate}$ being slightly higher in the on-mound core (4.4g/cm^2*kyr vs. 5.1g/cm^2*kyr), reflecting the higher ca$CaCO_3$ content in this core (Fig. 2.7).

2.5.4 Carbonate budget

The establishment of a full carbonate budget for the uppermost part of Propeller Mound is hampered by the incompleteness of the sediment record. Based on the preserved sediments, net carbonate accumulation through the last 175kyr is between 0.5kg/cm^2 (GeoB 6728-1 and GeoB 6729-1) and 2.1kg/cm^2 (GeoB 6730-1), with approximately ⅓ of these values attributable to coral carbonate. These values are rather low and the total accumulation rates are even lower than in the off-mound sediments.

This observation sheds some light on Propeller Mound as an individual mound but not on the sedimentation on carbonate mounds in general. The comparison of off-mound and on-mound sediment accumulation in the Propeller Mound area indicates that on a Late Pleistocene time scale the mound is even shrinking relative to the surrounding sediments, which is most likely due to ongoing erosion on the mound. However, there must have been a different setting in the history of Propeller Mound; otherwise it would not be a mound.

Coral growth on a mound is assumed to increase the sedimentation of allochthonous material by creating a low-energy micro environment among the corals – enhancing the deposition of suspended material brought along by bottom currents (Freiwald and Shipboard scientific crew 2002). Indeed, the sediments deposited under such conditions are noticeably finer grained than those deposited in areas barren of corals (Dorschel, unpubl. data). Thus, by the contribution of coral material and an enhanced amount of fine sediments, coral growth on a carbonate mound should significantly enhance total accumulation.

Seismic investigations in the near-by Belgica Mound province in the eastern Porcupine Seabight show that the carbonate mounds must have grown extremely rapidly during their initial stages, as it is indicated by onlap and moat structures in the surrounding sediments (van Rooij et al. 2003). Later during their development, the growth rate seems to have decreased. Slightly to the north of the Hovland Mound province, to which Propeller

Mound also belongs, the final stage of carbonate mound development can be seen. There, in the Magellan Mound province, a huge amount of carbonate mounds totally buried by sediments has been detected in seismic surveys (Henriet et al. 1998; De Mol et al. 2002; Huvenne et al. 2002).

Propeller Mound might also fit into such a scenario, as it possibly represents a carbonate mound at the turn from a (slow) growing carbonate mound to a mound in the stage of being buried by hemipelagic sediments. The lower accumulation rates compared to the off-mound sediments supports the conclusion that Propeller Mound has already entered the stage of decline and if this development continues into the future, Propeller Mound will follow the fate of the already buried Magellan Mounds.

2.6 CONCLUSIONS

Propeller Mound has a carbonate content of >50%, with a significant component consisting of fragments of the cold-water corals *L. pertusa* and *M. oculata*. Extrapolating these results to other elevated structures in the Porcupine Seabight and adjacent regions, the term cold-water coral carbonate mounds, or simply carbonate mounds, seems to be well justified. Unfortunately, the complex sedimentation and erosion pattern on Propeller Mound prevent the establishment of a quantitative carbonate budget. However, some qualitative conclusions can be drawn. It is obvious that ~20% of coral carbonate found on the mound are unique to these kind of structures compared to the “normal” sea floor around them. In addition, it is very likely that the corals act as a sediment baffler, thereby adding another portion to the hemipelagic background sedimentation. Thus, based on the available data, the net effect of coral growth on the accumulation of carbonate on mounds can be given with 15%+X. Future analyses on carbonate mounds still in the growth phase will help to better quantify their carbonate and their overall sediment budget.

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DEGLACIAL SWEEPING OF A DEEP-WATER CARBONATE MOUND

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Abstract

Since their first detailed scientific description (Hovland et al. 1994) in 1994 the deep-water carbonate mounds on the Celtic continental slope off Ireland have received considerable scientific interest (Henriet et al. 1998; De Mol et al. 2002; Kenyon et al. 2003; van Weering et al. 2003). Their almost exclusive occurrence in hydrocarbon exploration areas raised the question to what extent these mounds are related to escaping fluids or gases from the sediments (Hovland et al. 1994; Henriet et al. 1998). An alternative hypothesis relates these mounds, which rise a few hundred meters above the surrounding seafloor (De Mol et al. 2002; Kenyon et al. 2003), solely to environmental forcing, that supports the rich deep-water coral ecosystems thriving on these mounds (Freiwald 2002). Analyses of these carbonate mounds are until now mainly based on seismo-acoustic studies (Hovland et al. 1994; Henriet et al. 1998; Huvenne et al. 2003; van Rooij et al. 2003; van Weering et al. 2003), with only a limited number of sediment samples being available (Coles et al. 1996; De Mol et al. 2002). Here we present the first detailed stratigraphic analysis of Late Quaternary sediments recovered from a carbonate mound in the Porcupine Seabight (Fig. 3.1) indicating that its uppermost sedimentary sequence is characterised by numerous hiatuses. These are most likely related to sweeping of the mound in turn with the re-establishment of interglacial circulation patterns and strongly point to environmental forcing as the dominant mechanism shaping deep-water carbonate mounds during the Late Quaternary.

Here we focus on Propeller Mound which belongs to the Hovland Mound Province, one of three mound provinces found in the Porcupine Seabight (van Rooij et al. 2003) (Fig. 3.1). While the Belgica Mounds in the eastern and the Hovland Mounds in the northern Porcupine Seabight form large conical or composite elevations above the seafloor, the Magellan Mounds found slightly northward of the Hovland Mounds are totally buried by sediments (De Mol et al. 2002). Propeller Mound has been sampled with three so-called on-mound sediment cores. An additional reference sediment core has been collected from the normal seafloor adjacent Propeller Mound. (Fig. 3.1). While this off-mound core consists of typical hemipelagic background sediments, the on-mound cores additionally contain 5-18% coral fragments, with core sections totally barren of corals being very rare (Dorschel et al. chapter 2).

For the off-mound core, stable oxygen isotope data, obtained on the benthic foraminifera *Cibicides sp.,* display a typical record reaching slightly further back than the last glacial maximum (Fig. 3.2). This interpretation is corroborated by a detailed correlation using Ca-records to two nearby cores dated by ^{14}C (chapter 2) indicating that the off-mound core represents a rather continuous paleoenvrionmental record covering the last ~27kyr. According to extensive AMS ^{14}C and U/Th dating the on-mound sediments reach back to >250kyrs (Fig. 3.2), thereby only providing strongly condensed or fragmentary sections. The different ages at the top of the on-mound cores as well as the varying and comparatively low inferred sedimentation rates of the individual core sections point to the presence of numerous hiatuses in these records. As such hiatuses occur in all three on-mound cores, they seem to be typical for Propeller Mound and probably also for other carbonate mounds. Thus, the key to understanding the Late Quaternary development of Propeller Mound in particular and of similar carbonate mounds in general is to unravel the processes causing these hiatuses.

A closer look at the on-mound core GeoB 6730-1 reveals that these hiatuses, most of them indicated by sudden shifts in the $\delta^{18}O$ data, are characterized by distinct peaks of coarse (>250µm) lithic grains (Fig. 3.3). In the Porcupine Seabight such coarse grains almost exclusively reach the sea floor as ice rafted detritus (IRD) during glacial times, as indicated by the continuous presence of IRD in the glacial section (>1.4m core depth) of the off-mound core GeoB 6718-2 (Fig. 3.3). The concentration of this coarse material in distinct layers in the on-mound core GeoB 6730-1 points to winnowing as an important factor contributing to the generation of the hiatuses.

Another suggestion of to the processes causing the hiatuses is provided by the $\delta^{18}O$ data. The off-mound core shows that in the northern Porcupine Seabight fully-glacial sediments are

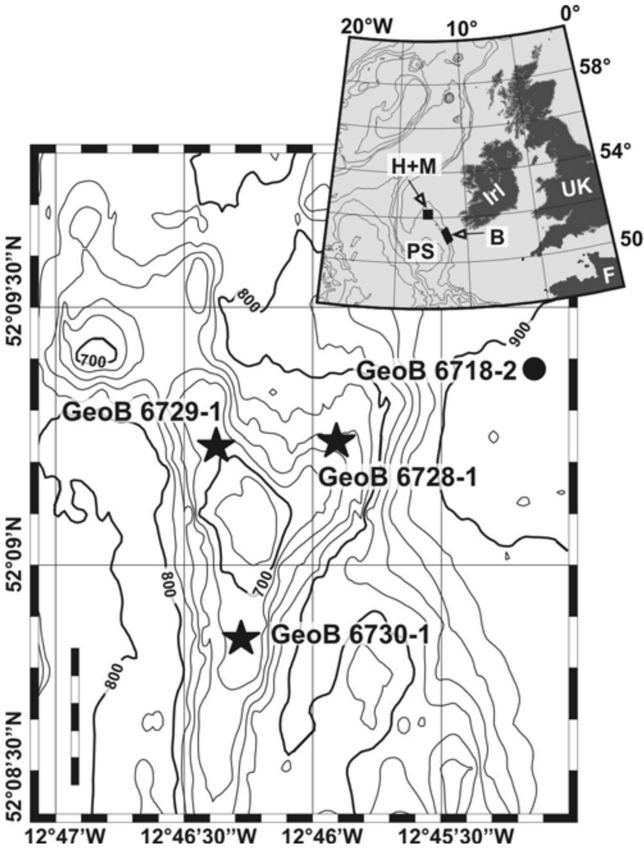

Fig. 3.1 Overview map showing the area of Propeller Mound, a deep-sea carbonate mound, in the Hovland mound province. The positions of the investigated on-mound sediment cores (stars) and the off-mound core (dot) are indicated. The total length of the scale bar corresponds to 500 m and the depth contours are given in meters. The inset shows the position of the Hovland (H), the Magellan (M) and the Belgica (B) mound provinces in the Porcupine Seabight (PS) in the North Atlantic off Ireland.

characterized by δ^{18}O values >3‰ PDB, while Holocene interglacial δ^{18}O values are below a threshold of <2‰ PDB (Fig. 3.2). The two excursions to heavy values in the Holocene sequence of GeoB 6718-2 are most certainly due to bioturbation, transferring the dominantly glacial foraminifer *C. kullenbergi* into the Holocene sequences (Rüggeberg et al. chapter 4).

Using the δ^{18}O boundaries defined by the off-mound core (interglacial <2‰ PDB; glacial >3‰ PDB), the preserved on-mound sediment intervals show that only in core GeoB 6730-1 are the top 53cm characterised by clearly interglacial values (<1.6‰PDB) and the interval 133–163cm reveals slightly heavier, glacial values (3.0–3.4‰ PDB) (Fig. 3.2). Thus, at all three on-mound sites almost only interstadial sequences with δ^{18}O values mostly between 2 and 3‰ PDB are preserved and almost all fully-glacial and fully-interglacial sediments either have not been deposited or must have been removed after deposition.

Under recent – interglacial – conditions, the dominant water mass interfering with the carbonate mounds in the Porcupine Seabight is the contour-following branch of the Mediterranean Outflow Water (MOW) (White 2001). Among the carbonate mounds in the Porcupine Seabight relatively high current velocities of >20m/s (D.H., unpubl. data) are reflected in typical bedforms associated with strong bottom currents as e.g. dunes, sand waves and gravel ridges, which prevail around the carbonate mounds in large parts of the Porcupine Seabight (Kenyon et al. 1998; Akhmetzhanov et al. 2001; Beyer et al. 2003).

An extensive study of cold water coral occurrences along the entire Atlantic margin of Europe (Freiwald 2002) concluded that most cold water corals in this region are confined to the MOW. This environment is probably associated with enhanced food concentrations related to the accumulation of sinking particles on the pycnocline between the dense MOW and the overlying Eastern North Atlantic Water (ENAW) (White 2001). In addition, internal tidal currents, trapped waves and baroclinic motions intensified at the pycnocline reported from this region (White 2001) might further increase food availability for the corals by repeated pumping of particles through the coral thickets.

However, under glacial conditions with sealevel lowered by ~120m, the exchange between the Atlantic and the Mediterranean through the narrow Strait of Gibraltar was significantly reduced. Thus, during the Last Glacial Maximum (LGM), the density-defined flow path of the MOW was quite different and did not reach further north than 40°N (Schönfeld and Zahn 2000).

The absence of the MOW in the Porcupine Seabight during glacial times changed the entire environmental setting in the mound provinces. Detailed analyses of grain-size distributions of the <160µm fraction, already highly susceptible to bottom current strengths of >20cms^{-1}, in the off-mound core revealed much finer sediments under glacial conditions compared to the prevailing interglacial (Fig. 3.3), implying that during the LGM bottom currents in the mound provinces were much weaker, i.e. slower than today. Enhanced deposition of fine-grained terrigenious material (associated with some IRD) as well as reduced bottom current activity result in a rather unfavourable setting for the corals (Freiwald 2002).

In addition, due to the replacement of the MOW and the ENAW by a homogenous water mass termed Glacial North Atlantic Intermediate Water (GNAIW) (Manighetti and McCave 1995) the pycnocline enhancing the food supply for the corals was absent. These changes had a profound impact on the living conditions of cold water corals and on the sedimentary setting on the carbonate mounds. The sediment baffling corals disappeared and no coral framework was developed to stabilise the fine-grained sediments deposited under

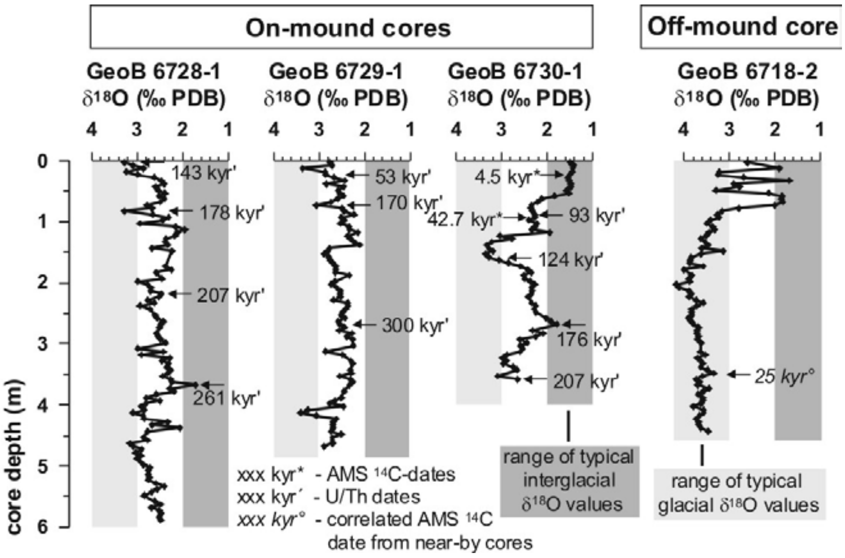

Fig. 3.2 Stable oxygen isotope ($\delta^{18}O$) data from the on-mound and off-mound sediment cores from the Propeller Mound area, northern Porcupine Seabight. The $\delta^{18}O$ data have been analysed on ~5 individuals of the benthic foraminifera Cibicides sp. following standard procedures (van den Bergh et al. 2003). The age assignments have been taken from ref. (Dorschel et al. chapter2). Dark and light shaded signatures indicate the range of typical glacial (>3‰ PDB) and interglacial (<2‰ PDB) $\delta^{18}O$ values, respectively.

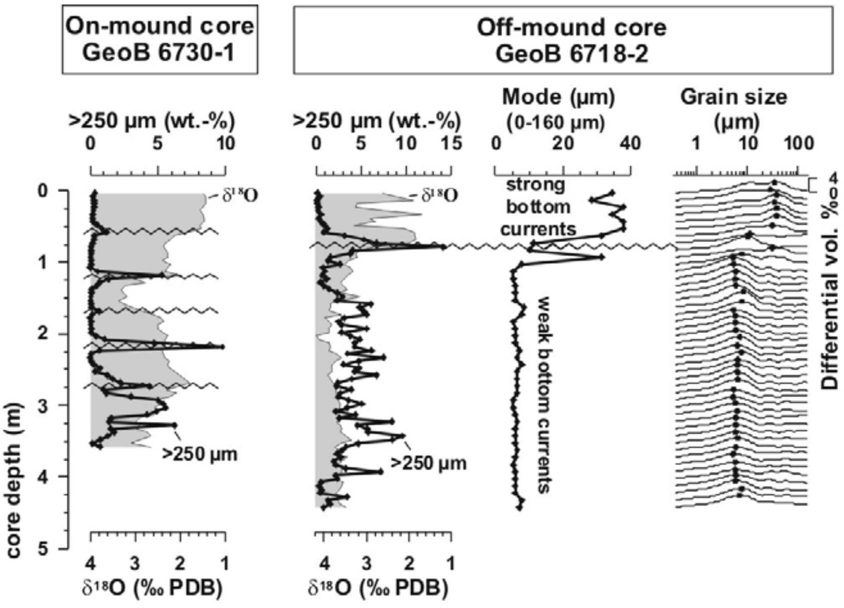

Fig. 3.3 Grain size and $\delta^{18}O$ data from an on-mound and an off-mound sediment core from the Propeller Mound area, northern Porcupine Seabight. Grain-size analyses revealed that peaks in the >250µm fraction, sieved from a decalcified sample, are often associated with jumps in the $\delta^{18}O$ records (shaded curves). These peaks are interpreted to reflect hiatuses, indicated by the wavy line. Continuously high proportions of the >250µm fraction, as found in the glacial section of off-mound core GeoB 6718-2, are typical for IRD-bearing sediments. The mode of the 0-160µm fraction, obtained by standard procedures using a Coulter laser particle sizer (Van den Bergh et al. 2003), has been determined for the terrigenous, carbonate-free portion of the sediments. High modes are assumed to reflect strong bottom currents and vice versa. As not all individual samples have a clear unimodal grain size distribution also the whole grain size spectra (0-160µm) for the samples are shown with the respective modes are indicated by black dots.

glacial conditions (Fig. 3.4). To date, no coral fragment with an LGM age has been collected from the Celtic margin, indicating that indeed no corals lived in this region under such conditions.

In the course of deglaciation, in turn with the rising sealevel, the MOW regained its present characteristics and began to sweep the mound provinces in the Porcupine Seabight. Especially on the carbonate mounds, where the currents are focused, as indicated by numerous moats around them (De Mol et al. 2002; van Rooij et al. 2003), the unstabilised fine-grained glacial sediments were easily winnowed (Fig. 3.4). Depending on current strength only the coarsest material stays in place as a lag sediment. At Propeller Mound these layers of coarse lag sediment (Fig. 3.3) indicate the position of the hiatuses attributed to the reestablishment of regional MOW circulation. Off-mound sediments also seem to have experienced some winnowing during the last deglaciation, indicated by a hiatus in our off-mound core at the respective core depth (Fig. 3.3).

Moreover, outcropping hardgrounds at the flanks of Propeller and other mounds observed on video-tapes (A.F. unpubl. data) provide clear evidence for flank erosion. This flank erosion can result in slope failure and subsequent mass wasting (Fig. 3.4), reflected by (a) the high spatial variability of the mound sediments hampering any correlation among the on-mound cores, (b) the relatively old ages at the top of the two flank on-mound cores GeoB 6728-1 and 6729-1, and (c) the rare occurrence of dropstones on the mounds compared to the dropstone pavement found at the mound base (A.F., unpubl. data).

After the removal of glacial sediments from the mounds down to a level where corals have again stabilised the sediments, the continuous presence of a strong interglacial MOW almost hindered the deposition of fine interglacial sediments, while coral growth was supported (Fig. 3.4). Baffling of some fine material among the corals may have taken place, but continuous sedimentation of fine material was mostly restricted to interstadials, as indicated by the $\delta^{18}O$ data. Thus, the best conditions for real mound growth probably existed during interstadials, when the interplay between bottom current strength, food supply, coral growth, and hemipelagic sedimentation produced those sediment sequences still preserved at Propeller Mound.

Through the last 300,000 years, net sedimentation on Propeller Mound is by far lower compared to the surrounding off-mound sediments. Thus, at least over this time span the mound is shrinking relative to the seafloor around it and if this scenario continues into the future, Propeller Mound will be buried and follow the fate of the already buried near-by Magellan Mounds.

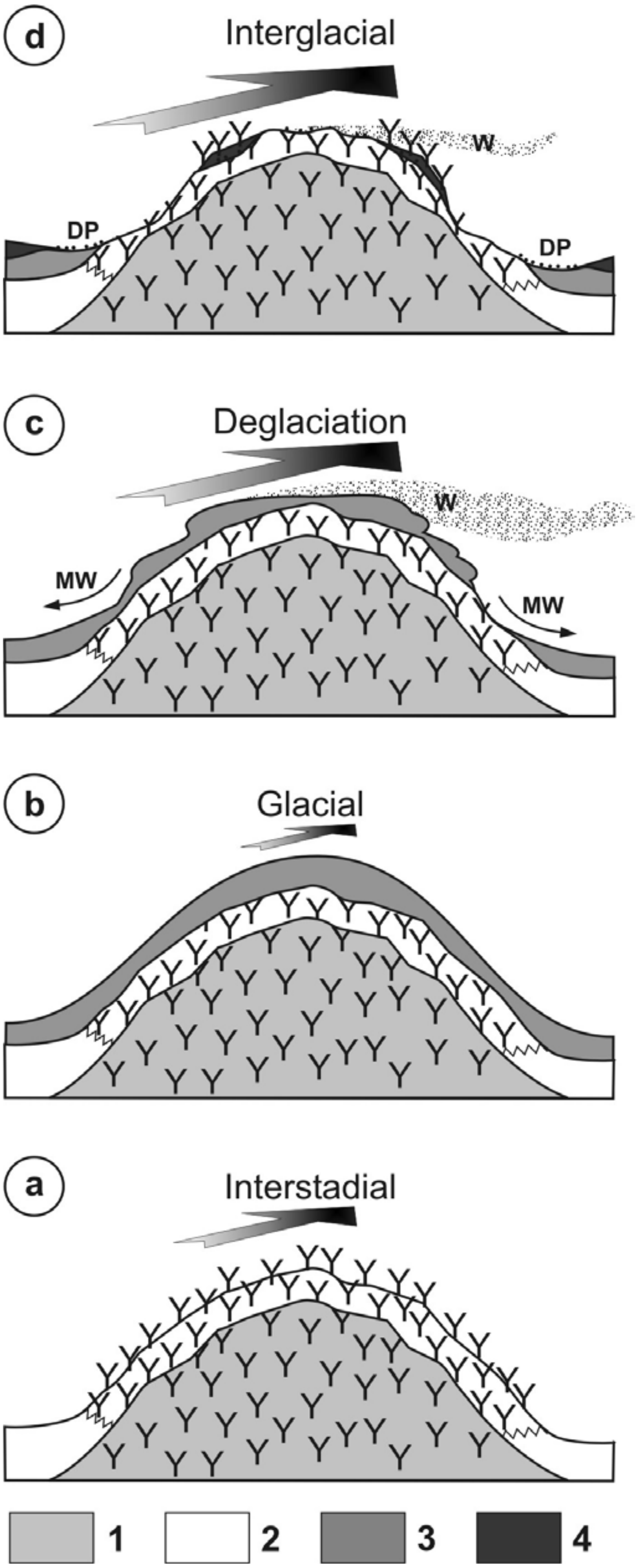

Fig. 3.4 Model for the Late Quaternary development of Propeller Mound and probably other deep-water carbonate mounds in the NE-Atlantic. The four stages (a-d) describe the temporal sequence of different settings mainly forced by the presence/absence of the Mediterranean Outflow Water and the resulting variations in bottom current strengths, indicated by the arrow size. Y – corals, W – winnowing, MW – mass wasting, DP – drop stone pavements in the moats, 1 – carbonate mound at begin of the sequence, 2 – interstadial sediments, 3 – glacial sediments, 4 – interglacial sediments.

These results also shed some light on the long-term development of deep-sea carbonate mounds. A recent model (Henriet et al. 2002) for the development of such carbonate mounds differentiates between (a) a trigger stage, during which a solid substratum for the initial settling of coral larvae is formed, (b) a booster stage, representing a period of fast mound growth as indicated by on-lapping sediment layers in the surrounding drift sediments (van Rooij et al. 2003), (c) a coral bank stage reflecting a mature carbonate mound and (d) a burial stage, when mound growth cannot keep pace with hemipelagic sedimentation around the mound. The pure size of the carbonate mounds testifies a phase of rapid growth (i.e. the booster stage), while the results obtained from Propeller Mound indicate this mound to be a prime example for a carbonate mound at the turn from the coral bank stage to the burial stage, thereby providing support for the mound development model (Henriet et al. 2002) described above.

Finally, our data clearly show the dominance of environmental forcing in shaping the carbonate mounds – at least for their youngest history in the Late Quaternary. However, as long as the bases of carbonate mounds have not been sampled, which can only be done by drilling, the question of whether or not hydrocarbon seeping is involved in the initial formation of these mounds has to remain unanswered.

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ENVIRONMENTAL CHANGES AND GROWTH HISTORY OF A COLD-WATER CARBONATE MOUND (PROPELLER MOUND, PORCUPINE SEABIGHT)

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Abstract

On- and off-mound sediment cores from Propeller Mound (Hovland Mound province, Porcupine Seabight) were analysed to better understand the evolution of a carbonate mound. The evaluation of benthic foraminiferal assemblages from the off-mound position helps to determine the changes of the environmental controls of Propeller Mound in glacial and interglacial times. Two different assemblages describe the Holocene and Marine Isotope Stage (MIS) 2 and late MIS 3 (~31kyr BP). The different assemblages are related to changes in oceanographic conditions, surface productivity and the waxing and waning of the British Irish Ice Sheet (BIIS) during the last glacial stages. The Holocene assemblage is related to a higher supply of organic material and stronger current intensities in water depths of recent coral growth. During the last glaciation the benthic faunas show high abundances of cassidulinid species, implying cold bottom waters and a reduced productivity. High sedimentation rates and the domination of *Elphidium excavatum* point to shelf erosion related to sea-level lowering (approx. 50m) and the progradation of the BIIS onto the shelf. A different assemblage described for the on-mound core is dominated by *Discanomalina coronata*, *Gavelinopsis translucens*, *Planulina ariminensis*, *Cibicides lobatulus* and to a lower degree by *Hyrrokkin sarcophaga*. These species are only found or show significantly higher

relative abundances in on-mound samples. This assemblage indicates a higher coral growth density on Propeller Mound in an earlier period, but is less abundant during the Holocene.

The data imply that the growth of the cold-water coral reef dominated by *Lophelia pertusa* on tops of the mounds is dependant on distinct oceanographic conditions. A Late Pleistocene decrease is observed in mound growth for Propeller Mound, which might face its complete burial in the future as has already happened to the buried mounds of the Magellan Mound Province ~10 nautical miles further to the north.

4.1 INTRODUCTION

4.1.1 Regional setting

Carbonate mounds along the European continental margin have been the subject of intense research during the past decade. In this paper we discuss the environmental setting of a carbonate mound in the Porcupine Sea Bight (PSB), which has been intensively sampled and studied during two cruises in the years 2000 and 2002 (Freiwald et al. 2000; Freiwald and Shipboard scientific crew 2002; De Mol 2002; De Mol et al. 2002). The object of interest is Propeller Mound, which is part of a cluster of highly-elevated mounds (up to 150m) in the Hovland Mound Province (Fig. 4.1). North of this area, seismic surveys detected a cluster of buried mounds – the Magellan Mound province (Huvenne et al. 2002; De Mol 2002) indicating sediment transport from the surrounding shallower shelf areas. The eastern slope of the PSB to the SE of the Hovland and Magellan Mounds is the location of the Belgica Mound province, including mounds up to 190m high (Henriet et al. 1998; De Mol et al. 2002).

Propeller Mound shows strongly current induced features, such as its N-S elongation, the steep flanks (up to 45°) and the moats around the foot of the mound (De Mol 2002; Freiwald 2002). Under-water investigations using the CHEROKEE ROV of the Bremen group (Freiwald and Shipboard scientific crew 2002) clearly show the sediment distribution on the mound. It is mainly covered by dead coral debris in a sandy silty matrix. Recent coral growth is restricted to the upper flank of the mound (690–710m water depth), where a dense living coral ecosystem occurs. However, close to the studied on-mound core GeoB 6730-1 (Fig. 4.1) only patches of corals have been observed. The reefs on Propeller Mound are mainly built up by cold-water corals *Lophelia pertusa*, *Madrepora oculata* and to a minor degree by *Desmophyllum cristagalli* (Freiwald 2002).

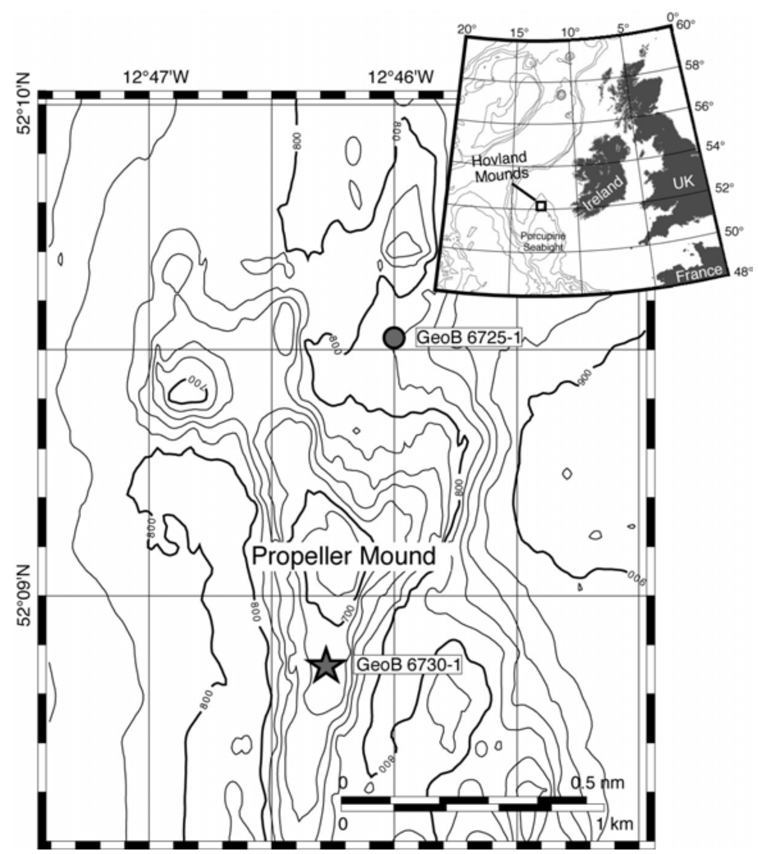

Fig. 4.1 Location map of Propeller Mound with sediment core sites analyzed within this study. Star = on-mound core GeoB 6730-1, circle = off-mound core GeoB 6725-1.

4.1.2 Recent oceanographic setting

Recent mound growth is strongly controlled by the present oceanographic setting, which is described in detail by White (submited). A generally northward transport of water masses west of Ireland is documented at the surface and in mid water depths (<1000m). In 600–800m, the depth of recent coral growth in the Hovland Mound province, a water mass boundary occurs between the Eastern North Atlantic Water (ENAW) and the Mediterranean Outflow Water (MOW). A branch of ENAW and MOW enters the PSB (Mohn 2000) and circulates topographically steered cyclonically along the slope within the PSB (Ellet et al. 1986). At the northern end of the PSB the currents weaken (1–5cm/s) and turn into a southward flow in the vicinity of the Hovland and Magellan Mounds (White 2001; submitted).

During RV POSEIDON cruise 265 in 2000, several CTD profiles above the Propeller Mound show an increase in salinity below 600m (De Mol 2002) indicating the ENAW–MOW pycnocline. Due to a strong density gradient at this water mass interface, organic material from the sea surface persists at this level for a longer time. In addition, organic material is also transported laterally within the PSB by currents generally circulating at around 5cm/s with maximum velocities up to 40cm/s (White 2001; White subm.). The corals benefit from this enrichment of food particles. It is obvious that water mass variations during glacial, when MOW did not reach the Porcupine Seabight (Schönfeld und Zahn 2000), had a great impact on coral growth and distribution.

4.1.3 Glacial oceanographic setting

The glacial oceanographical setting is not well studied in the PSB. The North Atlantic Polar Front was situated south during most of last glacial stages (Jones and Keen 1993). Surface water movement was reversed during glacials, flowing southward as a coastal current west off Ireland (Fig. 4.2; Sarnthein et al. 1995), leading to summer Sea Surface Temperatures (SST) of 5°C for the Last Glacial Maximum (LGM) (<6°C for most of MIS 3) and winter SST of 0–1°C (2–8°C MIS 3) (Sarnthein et al. 1995; Bowen et al. 2002). Glacial North Atlantic Intermediate Water (GNAIW) occurs in water depths down to 1700–2000m (Manighetti and McCave 1995) and flows from the north via the Wyville-Thomson Ridge and through the Rockall Trough to the south. According to Duplessy et al. (1988) and Oppo and Lehman (1993) the term GNAIW is used for mid-depth waters of uncertain origin. Its production occurs in the Norwegian Sea at least during MIS 2 via a mechanism strongly influenced by sea ice formation (Veum et al. 1992), but the composition of GNAIW may have changed during the glacial time with differing sources. An influence of the very cold GNAIW on the PSB is assumed. Schönfeld and Zahn (2000) describe a main glacial MOW flow up to 800m deeper than today, due to an increased density induced by a much higher salinity. In addition, the glacial flow pattern indicates no northward flow of MOW along the European continental margin and therefore no boundary between the glacial intermediate water mass and MOW existed in the PSB.

A maximum land ice extent of the BIIS probably reaching offshore W Ireland to the present 200m isobath is reported by Bowen et al. (2002) for MIS 4 (Fig. 4.2). During MIS 3 Ireland was covered with treeless, tundra-like vegetation (Jones and Keen 1993). An advance of land ice occurred around 30ka BP, covering most of Ireland (Knutz et al. 2001) synchronous with a sea-level lowering of around 50m (Lambeck et al. 2002). The southward flowing surface waters, land ice extension and calving of icebergs from Irish mainland as documented by iceberg plough marks on Slyne Ridge (Games 2001), as well as the sea-level lowering suggest an enormous increase in terrigenous sediment supply to the PSB (e.g. Auffret et al. 2002).

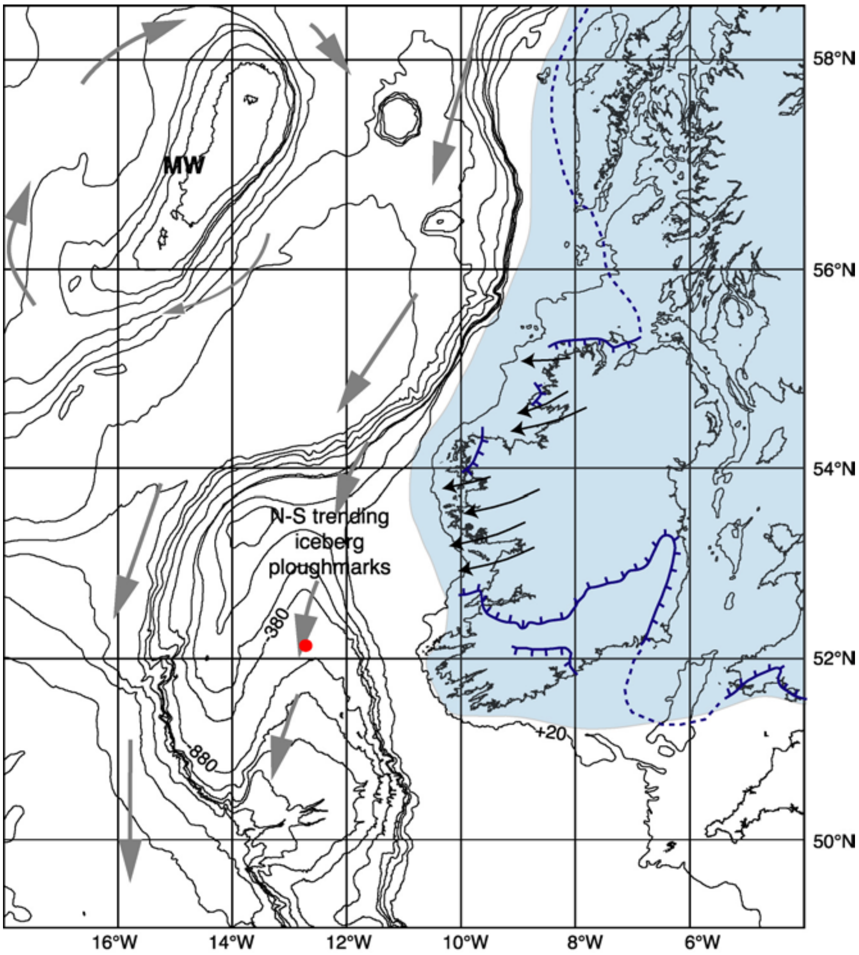

Fig. 4.2 General map of Ireland during glacial intervals. Indicated are ice limits (dark blue) and general ice flow (black arrows) for MIS 2 (after Eyles and McCabe 1989, Jones and Keen 1993), maximum land-ice extend (light blue) for MIS 4 (after Bowen et al. 2002), surface circulation (grey arrows) and melt water intrusion (MW) resulting in a week anticyclonic circulation around Rockall Bank for MIS 2 (after Sarnthein et al. 1995). N-S trending iceberg ploughmarks are reported on Slyne Ridge (after Games 2001). Glacial bathymetry corresponds to present-day water depth minus 120 m. Red dot marks the position of Propeller Mound.

4.1.4 Aim of study

The objectives of this study are to reconstruct the environmental setting of Propeller Mound for the past glacial-interglacial cycle, to resolve disturbances of the general sedimentation, related to episodes of sea-level lowering and advances of land ice masses on Ireland inducing calving of icebergs, as well as paleoceanographic changes between glacial–interglacial times. Therefore we produced stable oxygen isotope data, AMS ^{14}C and U/Th datings, total and organic carbon measurements, as well as the evaluation of benthic foraminiferal assemblages from an off- (core GeoB 6725-1) and an on-mound (core GeoB 6730-1) location.

4.2 MATERIALS AND METHODS

Two sediment cores from the Propeller Mound region, GeoB 6725-1 (off-mound position 52°09.52'N, 12°46.01'W; water depth 820m) and GeoB 6730-1 (on-mound position 52°08.86'N, 12°46.28'W; water depth 704m; see Fig. 4.1) were investigated. Both cores were sampled every 5cm using 10cm³ syringes. Each sample was weighed, carefully washed over 63µm sieves, dried at 50°C and weighed again. Thereafter all samples were dry sieved into fractions 63-125µm, 125-250µm, 250-500µm, 500-1000µm and >1000µm. Fractions >125µm were used for faunal analysis (Rüggeberg et al. in prep.). A taxonomic list of benthic foraminiferal species discussed in this study is given in Appendix 1. Species diversity is expressed in numbers of species corrected to an equal size of 100 specimens (Lutze 1980).

For the analysis of organic carbon (C_{org}) and total carbon (C_{total}), the samples were measured using a Carlo Erba NA-1500-CNS analyser at GEOMAR, Kiel. Organic carbon is determined after removing carbonate carbon by acidification with 0.01 N hydrochloric acid. Inorganic carbon was derived from the difference between total and organic carbon. Percent carbonate was calculated according to their atomic weight ratios as:

$$CaCO_3\ (\%) = 8.33*(C_{total} - C_{org}).$$

Stable oxygen isotopes ($\delta^{18}O$) were measured on three to five specimens of either the benthic foraminifera *Cibicidoides kullenbergi* or *Cibicidoides wuellerstorfi* (fraction 250-500µm) for both investigated cores. Additionally, 15 specimens per sample of planktic foraminifera *Globigerina bulloides* (fraction 250-315µm) have been analysed for their $\delta^{18}O$ composition for the top 120cm of the off-mound core GeoB 6725-1. The isotopic composition of the samples was carried out with a Finnigan MAT 251 mass spectrometer at the Isotope Lab Bremen University. A working standard (Burgbrohl CO_2 gas) was applied, which has been calibrated against PDB by using the NBS 18, 19 and 20 standards. Consequently, all $\delta^{18}O$ data given here are relative to the PDB standard. Analytical standard deviation is about ±0.07‰.

Age estimations in both cores are based on AMS ^{14}C datings using mono-species samples of planktic foraminifera species *Neogloboquadrina pachyderma* (either dextral or sinistral) from the fraction 125-250µm. Approximately 10mg of foraminiferal carbonate were analysed at the Leibniz Laboratory for Age Determinations and Isotope Research at the University of Kiel (Nadeau et al. 1997). After the correction for $\delta^{13}C$, the ^{14}C ages were calibrated to the calendar year scale by the Calib 4.3 program (Stuiver and Reimer 1993) using the marine data set of Stuiver et al. (1998) and a reservoir age of 400 years. Ages greater 21kyr BP were corrected using the method of Voelker et al. (1998) (Table 2.2 chapter 2).

In several depth intervals of core GeoB 6730-1 some coral fragments of *L. pertusa* were used to determine additional absolute ages using the U/Th ratio of the aragonite skeleton (Table 2.3 chapter 2). All samples were first ultrasonically cleaned and scrubbed with dental tools to remove exterior contaminants (iron-manganese crusts and coatings) from the fossil coral fragments as described in Cheng et al. (2000). When the coral looked clean under the binocular, each sample was bathed in 50/50 mixture of 30% peroxide and 1 M NaOH for 15 minutes with ultrasonification to remove organic stains left on the coral. This step already removed up to 50 % of the inner and outer coral skeleton. Therefore, the last step of the cleaning procedure described by Cheng et al. (2000), where the samples were submerged in a 50/50 mixture of 30% peroxide and 1% $HClO_4$ was skipped, otherwise no material would have been left for analysis. Before measurement using a Finnigan MAT 262 RPQ2+Thermal Ionisation Mass Spectrometer (TIMS) at GEOMAR Kiel, all samples were checked for the cleanness of the aragonite. Therefore a small amount of the samples was cut off before and after chemical and physical cleaning and was analysed using X-ray diffraction (XRD), to evaluate the chemical composition primarily of the aragonite skeleton after the whole procedure (100% aragonite in all samples).

4.3 RESULTS

4.3.1 Off-mound core GeoB 6725-1

Stratigraphy

Oxygen isotope data, carbon measurements, absolute abundance, as well as numbers of species of benthic foraminifera are illustrated in Fig. 4.3. The base of the core is disturbed by turbidites indicated by two sequences of upward fining sediments. Above this sequence the benthic $\delta^{18}O$ record shows low variability with values around 3.5‰ PDB. Planktic $\delta^{18}O$ measurements within the top 120cm present higher variability with values ranging between 0.7 and 3.3‰ PDB. Lower $\delta^{18}O$ values of *G. bulloides* are synchronous with higher carbonate content (35 wt.-%) of the foraminifera bearing sandy silt, whereas persistently low values of carbonate (20 wt.-%) were found in fine-grained, terrigenous sediments. The mean carbonate content of the off-mound core is 22.5 wt.-%. The absolute abundance and normalised number of species of benthic foraminifera follow this trend, showing highest values at the core top (>2000ind/g and >30 species per sample) and lowest values in the fine-grained material (100–200ind/g, 18–30 species per sample). Organic carbon contents (0.2–0.4 wt.-%) are low throughout the core, again with the highest values recorded at the core top.

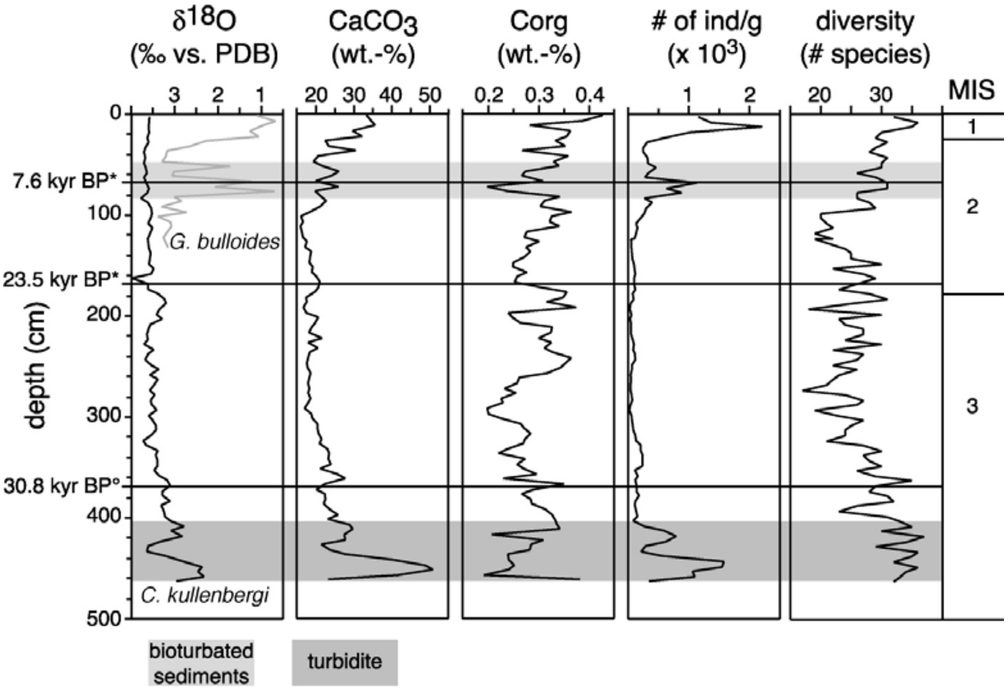

Fig. 4.3 Established stratigraphy of off-mound core GeoB 6725-1 from benthic and planktic oxygen isotope data, AMS ^{14}C dates as well as carbon measurements and inter-core correlation Dorschel et al. (chapter 2). Also indicated are concentrations of benthic foraminifera and numbers of species.

These data suggest a distribution into the youngest three marine isotope stages. Inter-core correlation of different off-mound cores (GeoB 6718-2, 6719-1) by Dorschel et al. (chapter 2) point out, that (1) a stratigraphic tie point, indicated by a characteristic double peak in the carbonate record, is probably related to Heinrich event H2 and its European precursor event, both dated to 23.7–25.6 cal. kyr BP (Bond and Lotti 1995; Grousset et al. 2000; Bowen et al. 2002), and (2) that the turbidite sequence below 404cm seems to be slightly older than 31 cal. kyr BP. The sedimentation rate decreases from >30cm/kyr for the late MIS 3 to 10cm/kyr for MIS 2, comparable to other near-shelf studies (e.g. Rasmussen et al. 2002b; Auffret et al. 2002; De Mol et al. 2002). The transition between MIS 2 and 3 (24 cal kyr BP) is set to 178cm as documented in AMS ^{14}C-date at 168cm and a slight decrease in the benthic δ^{18}O values. A Holocene layer in the top 23cm is indicated by lower δ^{18}O values of *G. bulloides*, which results into a sedimentation rate of 2–3cm/kyr assuming the core top reflects the present-day surface sediment. An additional AMS ^{14}C date at 68cm represents an age of 7.65 cal. kyr BP, pointing out an interval of heavily bioturbated sediments.

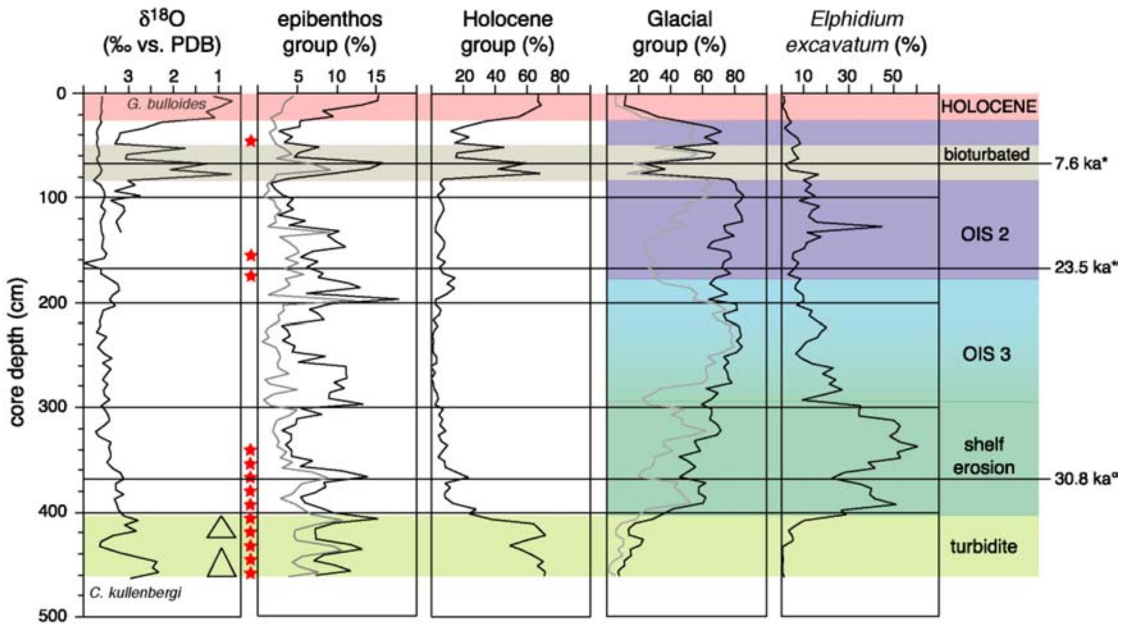

Fig. 4.4 Relative abundance of the *Holocene group* (*U. mediterranea, T. angulosa, M. barleeanum, H. balthica, B. robusta, B. marginata, C. laevigata, U. peregrina*), the *Glacial group* in black (*C. teretis* (in gray), *G. subglobosa, C. reniforme, C. kullenbergi, C. obtusa, S. woodi*) and the dominance of *E. excavatum* and *C. teretis* for late MIS 3) of core GeoB 6725-1. Epibenthic (black) and attached epibenthic species (gray) are according to Murray (1991) and Schönfeld (1997, 2002a). Red stars mark intervals with occurrence of coral fragments and other shell fragments, triangles show upward fining sediment, * = AMS ^{14}C dates, ° = inter-core corellation (Dorschel et al. this volume). Note: Relative abundance of *Holocene*, *Glacial group* and *C. teretis* are calculated without *E. excavatum* to the total assemblage.

Benthic foraminiferal assemblages

The faunal diversity of benthic foraminifera in off-mound core GeoB 6725-1 is expressed in species number referred to an equal sample size of 100 counted specimens (Fig. 4.3). The values range from 20 species within MIS 2 to 30 species during the Holocene.

Elphidium excavatum is highly abundant in off-mound core GeoB 6725-1, especially in the lower core section, where it exceeds 50% of total abundance (Fig. 4.4). This species is reported to live in shallow shelf areas generally above 200 m (Seidenkrantz et al. 2000), but is also found in greater depths to which it is often transported passively. It belongs to the epiphytic taxa (Seidenkrantz et al. 2000), whereas Murray (1991) describes non-keeled species of the genus *Elphidiidae* as infaunal, thriving free in mud and sand on the inner shelf. This species is most important in transitional cooling events (e.g. the Faeroe-Shetland Ridge, Rasmussen et al. 1996) and is extremely tolerant and adaptable to large variations in temperature, salinity and food supply (Linke and Lutze 1993). The abundance of *E. excavatum* is considered as an indication of erosional processes from shallow shelf areas and therefore not a part of the fossil community (Struck 1992). Its abundance is not included into the calculation of the relative abundance of the following two assemblages.

The benthic foraminiferal faunas of off-mound core GeoB 6725-1 show two different assemblages describing the glacial and the Holocene. The Glacial group is dominated by *Cassidulina teretis, Globocassidulina subglobosa, Cassidulina reniforme, C. kullenbergi* and subdominant species *Cassidulina obtusa* and *Sigmoilopsis woodi*. This assemblage increases continuously from ~40% during late MIS 3 (mainly described by *C. teretis*) to values >80% during MIS 2 (Fig. 4.4). *C. teretis* is the most abundant species in this assemblage, varying between ~30% during the onset of MIS 2 and >70% within the peak glaciation (Fig. 4.4). This species is reported as shallow infaunal (Murray 1991), but also as epifaunal on sponge needles (Altenbach 1992), and feeds on organic debris at the surface or in the uppermost layer of the sediment (Korsun and Polyak 1989). Mackensen and Hald (1988) describe *C. teretis* as a continental slope species, thriving in cold bottom waters (-1°C) and preferring fine-grained, organic rich, terrigenous mud. The onset of MIS 2 is characterised by increasing abundance of *G. subglobosa, C. reniforme, C. kullenbergi, C. obtusa*, and *S. woodi*, but their values decrease rapidly as *C. teretis* becomes more abundant (Fig. 4.4). Those species may be interpreted as an indicator for cold and nutrient poor bottom water conditions (Rasmussen et al. 2002b) and show an infaunal habitat. *G. subglobosa* is reported in higher oxygen levels of the sediment pore water compared to the cassidulinid species (Kaiho 1994), but also tolerates high environmental stress, especially variations in the oxygen content (Seidenkrantz et al. 2000).

The Holocene interval is dominated by *Uvigerina mediterranea* and *Trifarina angulosa*. Subdominant species are *Melonis barleeanum*, *Hyalinea balthica*, *Bulimina marginata*, *Uvigerina peregrina* and *Cassidulina laevigata* (Fig. 4.4). This assemblage (*Holocene group*) has a maximum relative abundance of 68% during the last 10kyr BP but rarely exceed 20% during MIS 2 or 3. In the bioturbated interval the *Holocene group* presents a comparable behaviour to the $\delta^{18}O$ record of *G. bulloides*, determining the existence of this heavily bioturbated section. Those species are reported as infaunal species (except *H. balthica*) living in muddy to fine sandy sediments (Murray 1991), whereas *T. angulosa* is associated with coarser sediments under the influence of stronger bottom currents (Mackensen et al. 1993, 1995; Rasmussen et al. 2002a).

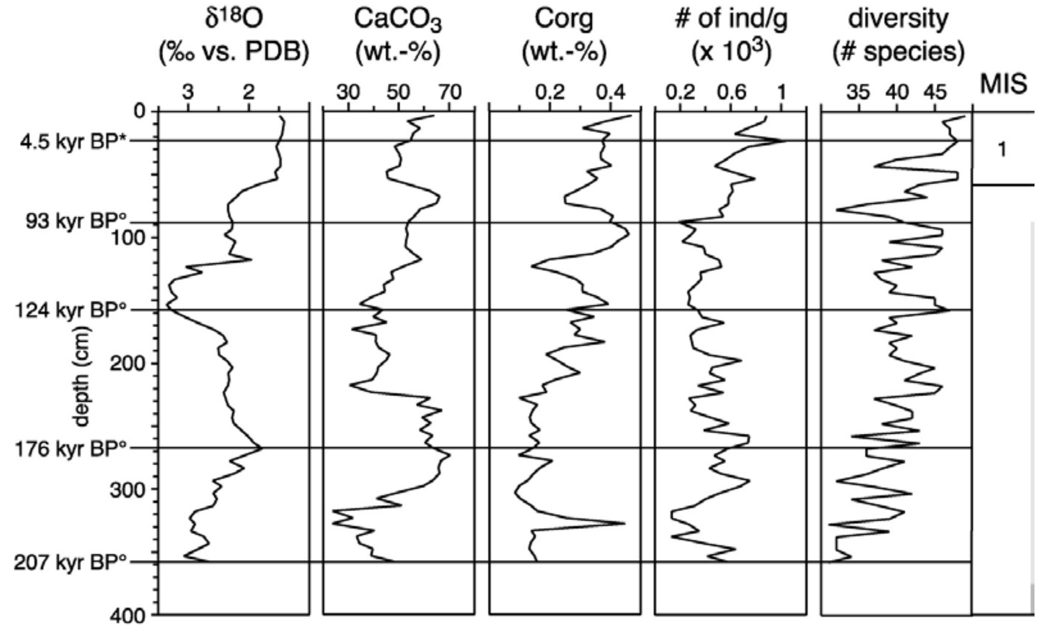

Fig. 4.5 Established stratigraphy for on-mound core GeoB 6730-1 from benthic oxygen isotope data, AMS ^{14}C and U/Th dates. Beside the records of carbonate and organic carbon content, concentrations of benthic foraminifera and number of species are illustrated.

4.3.2 On-mound core GeoB 6730-1

Stratigraphy

Fig. 4.5 presents oxygen isotope data of *C. kullenbergi*, carbon measurements and absolute abundance, as well as numbers of species of benthic foraminifera from on-mound core GeoB 6730-1. The δ^{18}O record is highly variable compared to the off-mound core, showing values between 1.4 and 3.4‰ PDB. In general, the carbonate content and absolute abundance of benthic foraminifera follows the δ^{18}O record with higher values during sections with low δ^{18}O values and vice versa. The carbonate content is more than twice as high as in the off-mound core (24–70 wt.-%, mean = 50 wt.-%), whereas organic carbon is generally in lower abundance with values ranging between 0.1 and 0.4 wt.-%. High numbers of species of benthic foraminifera (>45) occur at the core top and decrease towards the core base, but are generally higher diverse (mean = 40 species) than in off-mound core GeoB 6725-1 (mean = 27 species).

The low benthic δ^{18}O values within the top 60cm of the on-mound core GeoB 6730-1 as well as an AMS ^{14}C date of 4.5 cal. kyr BP at 23cm correspond to the Holocene interval (Fig. 4.5). Below the Holocene cover, the stable isotope record and several U/Th dates on coral fragments of *L. pertusa* indicate that the on-mound core is marked by numerous hiatuses with almost no fully interglacial sediments (expected $\delta^{18}O$ values of around 1.5‰ PDB), nor glacial sediments (expected $\delta^{18}O$ values of >3.5‰ PDB) being preserved (chapter 3). Most likely erosional processes on elevated mound areas with removal of nearly all glacial and interglacial sediments during phases of enhanced current intensity may have caused the hiatuses (chapter 3). Therefore core GeoB 6730-1 can only be divided into a Holocene cover and older sediments below.

Benthic foraminiferal assemblages

The faunal diversity (normalised species numbers) of the on-mound benthic foraminifera is much higher compared to the off-mound site GeoB 6725-1 (Fig. 4.6), showing values between 32 and 49. The dominance of individual species is generally lower (e.g. *C. teretis*: off-mound maximum >70% compared to on-mound maximum ~23%), which is also described by Coles et al. (1996) for their study in the northern PSB. This indicates that the coral ecosystem offers a habitable life for many more benthic species with both, an infaunal and epifaunal lifestyle. As the age model of on-mound core GeoB 6730-1 is insufficient to resolve glacial, interglacial or interstadial periods, the identified groups of the off-mound core are transferred to the counted on-mound species to get an idea of their distribution and variability (Fig. 4.6).

The *Glacial group* is less abundant in the on-mound record compared to core GeoB 6725-1. During the Holocene this group behaves similarly to the off- mound core with values between 10–20%, but it exceeds 20% only within four sections between 120–320cm, with maximum of 43% at 183cm (Fig. 4.6). Only these four sections show higher contributions of the *Glacial group*, but do not describe comparable abundances as in core GeoB 6725-1 with ~70% typical for fully glacial conditions. Both observations confirm the conclusion already mentioned above that interstadial sediments dominate the entire on-mound record below the Holocene layer (chapter 3). Neither glacial nor interglacial (Holocene) assemblages have a comparable high relative abundance as documented in core GeoB 6725-1.

The *Holocene group* is less abundant on-mound during the Holocene than in core GeoB 6725-1 with mean values of around 45% (Fig. 4.6). Maximum abundance (>40%) of this group occurs within the top 118cm and the section 323–358cm at the core base, but its abundance generally describes >20% throughout the entire core, except for section 178-193cm and 313cm. As this group represents high and more continuous flux of organic material within lower oxygen concentrated waters (see above), most of the sediments of the on-mound core can be related to warmer periods, at least interstadials.

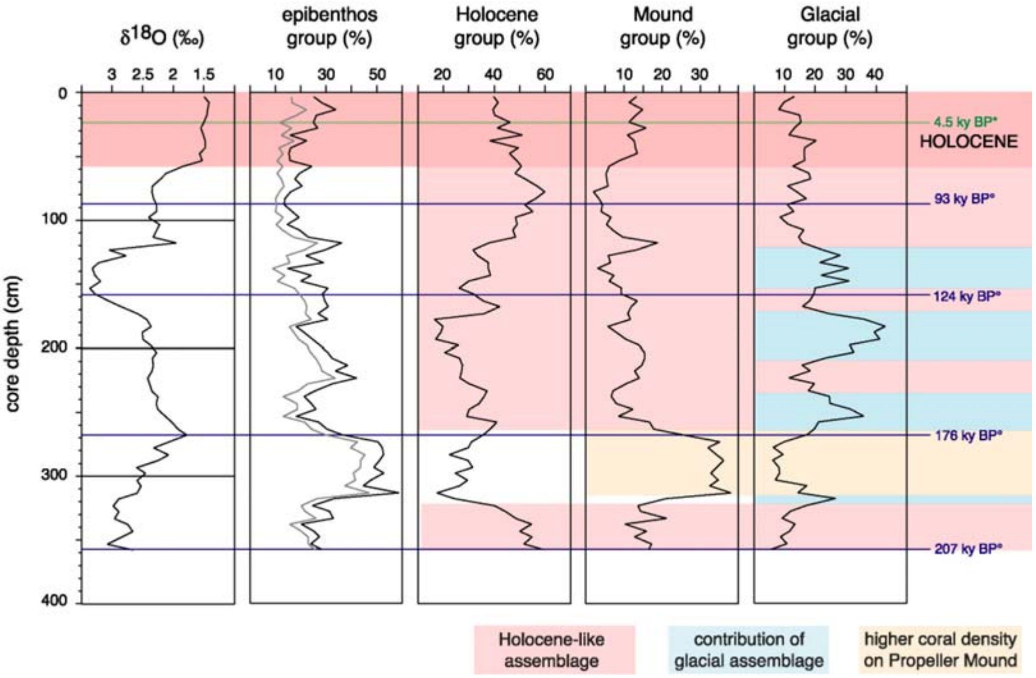

Fig. 4.6. Relative abundance of the off-mound-identified *Holocene group* and *Glacial group* transferred to on-mound core GeoB 6730-1, as well as the *Mound group* and epibenthos group. Higher abundance of each assemblage describes the different sections illustrated to the right. Epibenthic (black) and attached epibenthic species (gray) are according to Murray (1991) and Schönfeld (1997, 2002a). Dominant and subdominant species of the the *Mound group* are *D. coronata, G. translucens, C. lobatulus, H. sarcophaga, P. ariminensis, C. refulgens, T. bradyi*. AMS ^{14}C date of *N. pachyderma* is in green and U/Th dates of *L. pertusa* are shown in blue.

In the on-mound samples several species occur, which are not described for the off-mound core or only show accessory contribution (<1%) to the total assemblage (Rüggeberg et all. in prep.). These species (*Discanomalina coronata*, *Gavelinopsis translucens*, *Planulina ariminensis*, *Cibicides lobatulus*, *Trifarina bradyi* and minor species (<5%) *Cibicides refulgens* and *Hyrrokkin sarcophaga*) are also common elsewhere in the NE Atlantic, but as they are not recorded in off-mound samples, they are considered as another assemblage, referred to as *Mound group*. The record of this *Mound group* varies between 2 and 38% of the total assemblage showing maximum values downcore between 278–323cm. Some of these species also have been counted in off-mound samples, but show only a minor contribution and are related to transport or erosional processes from the mound. The record of epibenthic species and attached epibenthic species follows the distribution of the *Mound group* (Fig. 4.6), indicating that epibenthic and attached benthic foraminifera dominate the *Mound group*.

H. sarcophaga shows a minor contribution to this assemblage. This species lives attached on *L. pertusa* and shows a parasitic life style (Freiwald and Schönfeld 1996), but is rarely found in the samples. Some individuals of *H. sarcophaga* have been counted from

L. pertusa fragments in the fraction >1000µm. *D. coronata*, a big (>500µm) epifaunal species, is reported in waters with high bottom currents and coarse sediment (Schönfeld 1997; Schönfeld and Zahn 2000). Schönfeld (2002b) describes a group of elevated epibenthic species in the Gulf of Cadiz consisting of *Discanomalina semipunctata, G. translucens*, *P. ariminensis*, *C. lobatulus*, *C. refulgens* and others. He found coherence between the elevated epibenthos and current intensity of the upper MOW flow. As a similar group of species is described here, a higher current intensity and substrates elevated above the sea floor seem to be the controlling factor for the species of the *Mound group*. The Mound group can therefore be related to a higher coral growth density on Propeller Mound.

4.4 DISCUSSION

4.4.1 Environmental setting of Propeller Mound

The results of the distribution of distinct benthic foraminiferal assemblages from off-mound position help to understand the environmental setting of Propeller Mound. With the understanding of the environmental setting around Propeller Mound we take a closer look at the on-mound core to evaluate the growth history of the mound to times exceeding 31kyr BP.

Late MIS 3

The transition between MIS 3 and 2 is clearly visible in the abundance of *C. teretis* (Fig. 4.4). Its record decreases rapidly from >60% relative abundance during late MIS 3 to values around 35% for early MIS 2.

The lower core part is characterized by an enormous sediment supply to the off-mound position. The turbidite at the base of the off-mound core occurred at around 31kyr BP with sediments eroded and transported from the surrounding Irish Mainland shelf to the east and the Slyne Ridge to the north. Knutz et al. (2001) describe an abrupt increase in basaltic IRD at around 30kyr BP from a core at the Barra Fan, north of the PSB. They suggest that glaciers reached the shelf edge transporting terrigenous material from NW Britain into the Rockall Trough area. A similar event most certainly occurred further south taking the turbidite sequences at the base of the cores GeoB 6725-1 and GeoB 6719-1 into account (chapter 2). An advance of the BIIS towards the shelf edge not only released terrigenous material from Ireland also high amounts of shallower shelf sediments were transported slope downward.

The described high abundance of *E. excavatum* in the off-mound core is documented right after the turbidite (<31kyr BP). This species is widely distributed in shallow polar seas (Hald et al. 1994) and known as an extremely tolerant and opportunistic species (Conradsen

1993; Steinsund and Hald 1994 for *E. excavatum* f. *clavatum*). Maximum concentrations of *Elphidiidae* species are observed in the proximity of river estuaries in the Barents and Kara Sea and in areas with heaviest ice cover (Steinsund and Hald 1994) and are associated with near glacial environments (Nagy 1965; Hald et al. 1994). As high numbers of *E. excavatum* are described within sediments of the off-mound core with a very high sedimentation rate of ~30cm/kyr, shelf erosional processes continued between 31–24kyr BP, simultaneously with a sea-level lowering of around 50m (Lambeck et al. 2002) and the extension of the BIIS.

Additionally, the occurrence of coral fragments in off-mound core GeoB 6725-1 during late MIS 3 (red stars in Fig. 4.4) also suggests that these erosional processes may have affected the elevated mounds (or at least the flanks of the mounds) in the Hovland Mound province, contributing sediments to the off-mound location. Towards MIS 2 shelf erosion decreases, expressed in decreasing numbers of *E. excavatum* (increasing abundance of the *Glacial Group*) but probably still persisted to a lesser amount during MIS 2 (Fig. 4.4).

The last glacial stage

During the last glacial stage the shelf areas to the east and northeast were under the influence of the ice sheet on Ireland covering the shallow shelf, but to a lesser degree than during MIS 4 (Fig. 4.2). The transport of surface water was reversed compared to recent conditions bringing cold waters with winter sea-surface temperatures at around 0°C from the north to the south (Sarnthein et al. 1995). GNAIW is described as the prominent water mass present in the glacial North Atlantic down to 1700–2000m (Manighetti and McCave 1995). Its composition may have changed through the glacial time due to different sources, but a contribution of MOW can be excluded as its glacial flow pattern predominantly occurred towards the west (Schönfeld and Zahn 2000). High abundance of *C. teretis* and *C. reniforme*, which are reported in present-day polar regions (Korsun and Hald 2000), indicate this very cold bottom water mass (<4°C). A different composition and source of GNAIW is possibly indicated by increasing contribution of *C. obtusa*, *C. kullenbergi* and *G. subglobosa* to the *Glacial group* during the onset of MIS 2 (decreasing abundance of *C. teretis* in Fig 4.4). *C. obtusa* and *G. subglobosa* are reported with increasing abundance during the time of deglaciation and the Holocene at the Faeroe-Shetland Gateway (Rasmussen et al. 2002b). Those species probably show a slightly warmer water mass intrusion into the PSB from a more southerly origin. A shift to higher abundance of almost only *C. teretis* during the deglaciation is related to the intensified formation of the GNAIW in the Norwegian Sea (Manighetti and McCave 1995, Zimmermann 1982) and probably also occurred during late MIS 3 (Fig. 4.4).

The temperature range where *L. pertusa* is reported to live along the European continental margin is given by Freiwald (2002) as 6 to 12.5°C. The lower temperature limit corresponds to the occurrence of reefs offshore Norway. Minimum temperatures of *L. pertusa* within the PSB show slightly higher values of 7.5°C. As GNAIW is reported as the water mass in intermediate depth and the relation of the *Glacial group* to polar conditions, it is evident that the glacial oceanographic setting in the PSB is below the habitable limits of *L. pertusa*.

During MIS 2 higher abundances of epifaunal species in the off-mound core are not only an indication of increasing bottom current intensities. For example, Thomas et al. (1995) relate lower abundance of infaunal species (higher abundance of epifaunal taxa) to reduced amounts of organic material reaching the sea floor. Higher abundance of the epifaunal group in core GeoB 6725-1 during the MIS 2 and 3 (Fig. 4.4) may indicate low glacial surface productivity, but the variations of this group are small, rarely exceeding 10% of the total abundance and a correlation between C_{org} and the epibenthos group is not visible (Fig. 4.3 and 4.4). The influence of benthic foraminifera from the Propeller Mound within the off-mound sediments is low but not to be excluded. The variations in epibenthic species in the off-mound sample may therefore be the result of erosional features from the elevated mound during glacials. Oceanographic conditions were not favourable for corals to grow. Without any coral growth on Propeller Mound the sediments can be easily washed away, especially from the very steep flanks (chapter 3).

The Holocene

The benthic foraminiferal assemblage of the Holocene strongly reflects the present-day environmental conditions and oceanographic setting. Species of this group show a great affinity to a high and continuous flux of organic material to the sea floor (e.g. Loubere 1991; Mackensen et al. 1993; Schönfeld and Zahn 2000), which is most important for the distribution of recent *Uvigerina* (Altenbach et al. 1999, Thomas et al. 1995). *M. barleeanum* is also higher abundant in organic rich sediments, whereas it shows special demands on quality and concentration of food (Caralp 1989). A generally higher amount of organic material in sediments may be related to higher surface productivity during the Holocene interval, but a correlation between organic carbon content (C_{org}) in the sediment with species of the *Holocene group* does not exist.

The mixing of ENAW and MOW controls the present-day oceanography in 600 to 800m water depth, with the MOW being characterised by lower oxygen and higher salinity concentrations. All endobenthic species of the *Holocene group* also show an association with lower oxygen concentrations in the sediment pore water (Kaiho 1994; Brüchert et al. 2000; Seidenkrantz et al. 2000) and probably indicate this mixing process and the influence of MOW in the northern PSB during the Holocene. Higher abundance of epibenthic species and *T. angulosa* as well as coarser sediments of the Holocene samples indicate stronger bottom current conditions compared to the glacial, which is coherent with fine fraction analysis (sortable silt) from off-mound sediment cores (Rüggeberg et al. in prep.).

The Holocene setting with higher surface productivity and a water mass boundary and therefore higher amounts of organic material in the depth of recent coral growth, as well as stronger current intensities seem to be the controlling factor for the recent cold-water coral distribution on Propeller Mound and the Hovland Mound province.

4.4.2 The fate of the Propeller Mound

Higher abundances of epifaunal and attached species have been reported as an indicator for changing bottom current intensities (Lutze and Thiel 1989; Linke and Lutze 1993; Hald and Korsun 1997), especially for the MOW in the Gulf of Cadiz (Schönfeld 2002a, 2002b). As already mentioned, the abundance of infaunal versus epifaunal taxa is also related to the amount of organic material reaching the ocean bottom (Thomas et al. 1995). On Propeller Mound, where the coral ecosystem produces high amounts of elevated substrates (at least for interglacials or periods of intense coral growth), variations in attached epibenthic foraminifera are rather related to variations in current intensities than productivity. Weston (1985) describes a similar but living assemblage of benthic foraminifera like the *Mound group* at the eastern slope of the PSB, where even bigger mounds occur (but not reported in her study as the discovery of the Belgica Mounds occurred later in the past decade). These mounds of the Belgica Mound province show a much denser coral reef growth on their tops (De Mol et al. 2002). Stronger bottom currents in that area have been documented with mean velocities around 10cm/s, but still >30% of the measured values exceed 20cm/s (White 2001) and are profitable for the corals while feeding on organic material. This also suggests a more favourable habitat for attaching foraminifera on hard substrates, especially for *D. coronata*, *C. lobatulus*, *C. refulgens*, *H. sarcophaga* and *G. translucens*. During the Holocene these species are relatively rare in samples of the on-mound core and contribute 13% to the Holocene group. This observation is related to the restricted coverage of coral reefs on the mound. In a former period of the Late Pleistocene corresponding to the depth interval 278 to 323cm, Propeller Mound seemed to have had a much higher coral density than at present covering the entire top of the mound, which was favourable for species of the *Mound group* to settle and to live on the elevated coral. The recent or Late Pleistocene condition of the Propeller Mound describes a declining stage with a general decrease in coral growth. If this situation persists into the future, the sediment supply from the surrounding shallower shelf areas especially during transitions from interglacial (interstadial) to glacial stages (e.g. MIS 3/2) will also bury Propeller Mound.

4.5 CONCLUSIONS

During the past ~31kyr two different benthic foraminiferal assemblages of off-mound core GeoB 6725-1 (*Holocene group*, *Glacial group*) and the occurrence of *E. excavatum* are related to climatic changes resulting into a different oceanographic regime and variations of the BIIS. These changes are important for the PSB and the distribution of cold-water corals on top of the mounds. The high abundances of infaunal species during the Holocene describe the present-day situation with strong bottom currents and a high supply of organic material to the sea floor. During the Last Glacial Maximum a high abundance of cassidulinid species is related to cold bottom water mass and reduced productivity. The late MIS 3 documents a turbidite sequence induced by the advance of the BIIS as reported from a more northerly site. Increasing sedimentation and the occurrence of *E. excavatum* shows strong sediment erosion from surrounding shallow shelf areas.

By transferring the identified off-mound assemblages on-mound, a dominance of the *Holocene group* throughout the entire core is recorded, interrupted only by three sections with slightly higher amounts of the *Glacial group*. In comparison with the stable oxygen isotope record, the data imply that only interstadial sediments remain on-mound and fully glacial as well as peak interglacial sediments seem to be removed.

A third assemblage with species mostly described in on-mound samples characterises the coral density on Propeller Mound. Present-day coral growth is mainly restricted to the upper flank of Propeller Mound, which is also present in the decreased abundance of the *Mound group* during the Holocene. In an earlier period this group shows higher abundances, representing times, when the mound had a denser coral cover.

The established data imply a Late Pleistocene decrease of mound growth for Propeller Mound. If this situation persists, the Propeller Mound will be buried at some point in the future under sediments mainly supplied from the surrounding shelf areas, thus sharing the fate of the already buried Magellan Mounds further to the north.

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4.7 APPENDIX

Faunal reference list of benthic foraminiferal species considered in this paper (in alphabetical order):

Bulimina marginata d'ORBIGNY = *B. marginata* d'ORBIGNY, 1826. Feyling-Hanssen et al. (1971, pl. 6, figs. 17-20), Oki (1989, pl. 11, fig. 3), Collins (1989, pl. 1, fig. 4).

Cassidulina laevigata d'ORBIGNY = *C. laevigata* d'ORBIGNY, 1826. Feyling-Hanssen et al. (1971, pl. 7, figs. 20-21; pl. 18, fig. 12), Mackensen and Hald (1988, pl. 1, figs. 1-7), Schiebel (1992, pl. 2, fig. 11), Heß (1998, pl. 13, fig. 8).

Cassidulina obtusa WILLIAMSON = *C. obtusa* WILLIAMSON, 1858. Hald and Steinsund (1992, pl. 2, fig. 3), Gooday and Hughes (2002, pl. 2, fig. d).

Cassidulina reniforme NØRVANG = *C. reniforme* NØRVANG, 1945. Thomas et al. (1990, pl. 4, figs. 13-14; pl. 10, fig. 10).

Cassidulina teretis TAPPAN = *C. teretis* TAPPAN, 1951. Mackensen and Hald (1988, pl. 1, figs. 8-15), Gooday and Hughes (2002, pl. 2, fig. e).

Cibicides lobatulus (WALKER & JACOB) = *Nautilus lobatulus* WALKER & JACOB, 1889. Feyling-Hanssen *et al.* (1971, pl. 9, figs. 9-14), Thies (1991, pl. 17, fig. 4; pl. 18, figs. 1-20), Struck (1992, pl. 5, fig. 1), Schönfeld (2002, pl.1, figs. 2-3).

Cibicides refulgens MONTFORT = *C. refulgens* MONTFORT, 1808. Schönfeld (2002, pl.1, figs. 11-12), Weston (1985, pl. 2, fig. 8).

Cibicidoides kullenbergi (PARKER) = *Cibicides kullenbergi* PARKER, 1953. Caralp (1985, pl. 6, figs. 8-11).

Discanomalina coronata (PARKER and JONES) = *Anomalina coronata* PARKER and JONES, 1857. Schönfeld (2002, pl.1, fig. 14).

Elphidium excavatum (TERQUEM) = *Polystomella excavata* TERQUEM, 1875. Thomas et al. (1990, pl. 4, figs. 5-7; pl. 7, figs. 1-3; pl. 9, figs. 19-22), Thies (1991, pl. 19, fig. 5).

Gavelinopsis translucens (PHLEGER & PARKER) = *G. translucens* PHLEGER & PARKER, 1951. Gooday and Hughes (2002, pl. 1, fig. A), Heß (1998, pl. 15, figs. 1-2), Timm (1992, pl. 7, fig. 12), Schiebel (1992, pl. 4, fig. 5).

Globocassidulina subglobosa (BRADY) = *Cassidulina subglobosa* BRADY, 1881. Struck (1992, pl. 3, fig. 2), Timm (1992, pl. 6, fig. 20), Heß (1998, pl. 13, fig. 14), Ohkushi et al. (2000, pl. 2, fig. 8).

Hyalinea balthica (SCHRÖTER) = *Nautilus balthicus* SCHRÖTER, 1783. Oki (1989, pl. 17, fig. 6).

Hyrrokkin sarcophaga CEDHAGEN = *H. sarcophaga* CEDHAGEN, 1994. Freiwald and Schönfeld (1996, p. 202, fig. 2a; p. 205, fig. 5a)

Melonis barleeanum (WILLIAMSON) = *Nonionina barleeana* WILLIAMSON, 1858. Struck (1992, pl. 4, fig. 6), Timm (1992, pl. 6, fig. 6), Heß (1998, pl. 13, fig. 5).

Planulina ariminensis d'ORBIGNY = *P. ariminensis* d'ORBIGNY, 1826. Feyling-Hanssen et al. (1971, pl. 9, figs. 4-6), Heß (1998, pl. 16, fig. 8).

Sigmoilopsis woodi ATKINSON = *S. woodi* ATKINSON, 1968. Ellis and Messina (1940-1978: http://www.micropress.org/micropress/eandm/index.php3).

Trifarina angulosa (WILLIAMSON) = *Uvigerina angulosa* WILLIAMSON, 1858. Oki (1989, pl. 12, fig. 10), Schiebel (1992, pl. 3, fig. 1), Timm (1992, pl. 6, fig. 5).

Trifarina bradyi CUSHMAN = *T. bradyi* CUSHMAN, 1923. Weston (1985, pl. 1, fig. 5), Heß (1998, pl. 10, fig. 14).

Uvigerina mediterranea HOFKER = *U. mediterranea* HOFKER, 1932. Thies (1991, pl. 17, fig. 3), Schiebel (1992, pl. 3, fig. 7).

Uvigerina peregrina CUSHMAN = U. peregrina CUSHMAN, 1923. Feyling-Hanssen et al. (1971, pl. 7, figs. 9-11), Timm (1992, pl. 6, fig. 2), Heß (1998, pl. 11, figs. 2-3), Ohkushi et al. (2000, pl. 2, fig. 4).

CONCLUSIONS

This thesis provides the first sediment and carbonate budget estimations of a carbonate mound in the NE-Atlantic and the first reconstruction of its Late Quaternary history. Propeller Mound, located in the Porcupine Seabight ~90 nautical miles west of Southern-Ireland, has been studied with particular attention paid to carbonate and sediment accumulation and to on-mound sedimentary processes.

To call Propeller Mound a carbonate mound is clearly justified. The on-mound sediments consist mainly of calcium carbonate with average $CaCO_3$ contents between 53 and 57 wt-%. 4 to 5% of the carbonate signal is derived from detectable coral fragments. Comparison with background sediments indicates that approximately one third of the $CaCO_3$ signal is mound specific because of degraded coral-derived aragonite present in the fine fraction. Even this value is probably underestimated due to an unknown portion of hemipelagic sediments baffled from suspension by the corals.

Although corals increase sedimentation rates on the mound, long-term on-mound sediment accumulation is rather low. Over the last 175kyrs only a maximum of $2.2g/cm^2kyr$ bulk sediment and $1.2g/cm^2kyr$ $CaCO_3$ have accumulated on Propeller Mound. The contribution of coral fragments has been $<0.40g/cm^2kyr$. By comparison, in the areas adjacent to Propeller Mound, between 3.0 and $16.9g/cm^2kyr$ bulk sediment and between 1.1 and $4.4g/cm^2kyr$ carbonate have been accumulated during LGM/T1 and the Holocene. These data imply that although coral growth increases, the net carbonate accumulation on-mound by at least 15%, it still is lower than in the off-mound areas.

The low long term sediment and carbonate accumulation rates on Propeller Mound are related to numerous hiatuses. They interrupt the mound sequences and are detectable in the $\delta^{18}O$ record and are also marked by distinct peaks in coarse fraction ($>250\mu m$). These hiatuses are caused by intense winnowing and mass wasting due to strong currents at mound locations.

MOW creates the present day currents affecting Propeller Mound, which causes intense winnowing and erosion. During glacials, it was replaced by the cold and low velocity GNAIW. These changes in hydrographic conditions had a marked impact on on-mound sediment deposition and preservation as outlined in the following scenario.

During interstadials, the balance between sediment input and current intensity creates an environment suitable for corals to grow and sediments to be accumulated. Coral stabilised fine grained sediments are deposited, as recovered in the on-mound cores. In the glacials, when current intensities are decreased and sediment input is increased by IRD and shelf erosion, the corals disappear. The mound is capped by glacial sediments. With the re-occurrence of MOW and the re-establishment of an interglacial current regime at the deglaciation, the unconsolidated glacial sequences are easily winnowed. Erosion on the mound flanks is likely to cause mass wasting. The complete removal of sediment sequences down to at least those stabilised by corals, results in a patchy distribution of remaining sediments with high spatial and temporal variability. The component of the glacial sediment that cannot be removed by the intensified currents produces those coarse horizons detectable in the sedimentary record. When the MOW is fully established during interglacial, strong currents prevent deposition of the exclusively fine grained interglacial sediments. Only minor amounts of these sediments settle, baffled by coral thickets.

The model sufficiently describes sedimentary processes on Propeller Mound, and it is reasonable that it also proves valid for other mounds, although further high resolution studies on different mounds are necessary to enhance the models reliability. As currents appear to be the dominant influence on Propeller Mound, further investigation into local current regimes would be necessary for a better understanding of current-mound interaction. Work targeting this issue through a sedimentary and coral facies analysis is presently been undertaken by a current PhD in Bremen. Current meters deployed in the Porcupine Seabight during POLARSTERN cruise ARK XIX 3a (June 2003) will provide detailed information on the present hydrographic regime interacting with the carbonate mounds. In addition, to gain better understanding of past and recent conditions at carbonate mounds, cores preserving longer time sequences will be needed in order to reconstruct mound settings during different phases of mound ontogeny. Ideally, these would penetrate through the base of the mound and resolve the speculative hypotheses for mound initiation.

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